SYSTEMS ENGINEERING COMPETENCIES ESSENTIAL FOR MECHANICAL ENGINEERING GRADUATES

A Thesis

by

RACHAL ELIZABETH THOMASSIE

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Chair of Committee,	Timothy J. Jacobs
Committee Members,	Debra Fowler
	Richard Malak
Head of Department,	Timothy J. Jacobs

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ABSTRACT

Mechanical engineering has long been a prominent and popular field of study, preparing graduates for a variety of jobs and careers. This discipline is often described as “broad”; however, one topic that is lacking in undergraduate mechanical engineering programs is systems engineering. As mechanical engineering graduates enter an ever-increasing global workforce and environment of large-scale, interoperating systems, the need for systems engineering knowledge is becoming more important. This study explores systems engineering concepts used by graduates of mechanical engineering programs and recommended for inclusion in these programs. An educational, program level rubric describing learning outcomes for systems engineering concepts is provided as well as faculty feedback on systems engineering in mechanical engineering. Finally, an approach to curricular inclusion is offered.

DEDICATION

This thesis is dedicated to my Creator who has gifted me with the opportunities, aptitude, abilities, and interests that led to the pursuit of this study and the perseverance to complete it.

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

Page

1. INTRODUCTION

1.1 Background

Systems engineering is a specialized field integrating multiple disciplines to ensure successful development and operation of a system from a functional and life cycle perspective [1]. It is young discipline, emerging in the early 1900s, and became prominently used during World War II [2]. However, its need has risen substantially with the increasing complexity of human-designed systems. It is also important to further define systems engineering and distinguish it from other "systems" language. Systems Engineers historically have come from a traditional engineering discipline by degree. Over time in one's career, an engineer could move into a Systems Engineer role. With the expansive growth of this field in recent years, industry has identified a deficit in systems engineering knowledge from college graduates, witnessed by the topic's inclusion in conferences and publications [1], [3]-[9]. The importance of systems engineering can also be seen in the Accreditation Board for Engineering and Technology (ABET) criteria and the increase in professional and research activities related to systems engineering and systems thinking (explored further in the next chapter). The early 2000s saw significant growth in formalized systems engineering programs in an attempt to fill this void [1], [8]. The majority of these programs are at the graduate level. This may indicate the importance of traditional engineering education at the undergraduate level, leading to the idea of including systems engineering concepts in traditional engineering programs at the undergraduate level. One author states, "Each engineering specialist looks at systems engineering with a perspective most strongly from his or her own engineering discipline" [6].

One such traditional discipline that has a broad foundation and prepares graduates to enter a variety of industries and job functions is mechanical engineering. Mechanical engineering is a very versatile and empowering degree, developing graduates qualified to work in virtually any industry and among a wide variety of job functions. Graduates with a mechanical engineering degree will work in a systems environment, and as they rise to positions of leadership, will be responsible for a system of subsystems and rely on multiple functional teams to ensure success. Therefore having a competency in systems engineering provides more value to the graduate. Since this discipline produces the largest number of undergraduates and it is such a versatile degree, this is an ideal curriculum to approach with an investigation into systems engineering [10]. It is rather quite adept to incorporating such concepts. However, only one ABET-accredited mechanical engineering program includes formal systems engineering instruction which is comprised of only one course. Currently, no standard exists to guide the level of systems engineering that should be introduced to the students [8]. It is therefore a unique opportunity for the mechanical engineering discipline to determine how to weave systems thinking into the mechanical engineering curriculum to produce graduates capable of meeting industry's needs.

1.2 Research Objectives

The objective of this research is to identify the systems engineering competencies used by graduates of mechanical engineering programs and further refine the extent of their use. This study seeks to identify the level of systems engineering competency required (ie. awareness, implementation), at what point they become relevant in a person's career, and to what extent these concepts could be included in a mechanical engineering undergraduate curriculum. This research also explores current inclusion of systems engineering concepts in mechanical engineering undergraduate curriculum in the United States seeking to identify gaps between what is used by graduates and what is included in curricula. A secondary objective is to explore methods of inclusion in the curriculum. Missing concepts are identified followed by an approach to include them in the mechanical engineering undergraduate curriculum.

1.3 Research Question

The aim of this research is to study the importance of systems engineering concepts and systems thinking for graduates of mechanical engineering programs and if graduates are lacking in knowledge and skill in these areas. It is hypothesized that a gap exists between what mechanical engineering students know about systems engineering when they graduate and what they are expected to know in the engineering workplace. The intent is to identify which systems engineering competencies are needed by graduates of mechanical engineering undergraduate programs and which are missing from the curriculum. Methods to incorporate the identified concepts into a mechanical engineering curriculum and faculty perspectives on this topic are explored. The research questions are:

- Which systems engineering concepts do graduates of mechanical engineering programs use?
- To what depth do mechanical engineering graduates need to know or understand these concepts?
- To what extent to mechanical engineering undergraduate curricula contain these concepts?
- How can these concepts be included in the curricula?

1.4 Research Methodology

In order to identify which systems engineering concepts are used by mechanical engineering graduates, the target audience is surveyed with a questionnaire presenting systems engineering competencies. This survey questions which competencies are used by the graduate, when they were used in their career and to what level they were used. From the survey, specific competencies are identified as vital to graduates. Next, mechanical engineering curricula from top programs across the Unites States are explored for inclusion of systems engineering concepts. A comparison of discovered vital concepts to existing curricula is made and methods of inclusion are offered in consultation with mechanical engineering faculty.

1.5 Hypothesis

With the growth in complexity of engineered systems and the increase in systems engineering usage in industry, it is hypothesized that some level of systems engineering competency is vital to graduates of mechanical engineering programs and that such programs do not adequately prepare graduates in this area. It is expected that graduates of mechanical engineering programs will go on to work in an environment that either directly uses systems engineering or is influenced by systems engineering, and therefore having systems engineering competency is essential for the success of their career. The hypothesis is that a deficit in preparation of systems engineering concepts occurs during mechanical engineering undergraduate studies. It is predicted that the senior capstone design and mechanical engineering elective courses are the most fitting to incorporate systems engineering concepts, as well as co-curricular and interdisciplinary projects. Engineering education prepares the future engineer by adding tools to their toolbox. Mechanical engineering graduates today are entering the work environment with tools missing. This research will identify these tools and offer creative ways to transform mechanical engineering education with systems engineering tools. Results of this research can be applied to mechanical engineering programs at other institutions as well as tailored to other traditional engineering disciplines.

2. LITERATURE REVIEW

2.1 Defining Systems Engineering

Systems engineering, while the term has been around for nearly a century, is still poorly understood or completely misunderstood today. With the emergence of larger, more complex systems, “systems” has become almost a buzz word, along with systems thinking. A brief history of the discipline and its expansive growth in the last few decades is presented. The nuanced differences in definition are also discussed.

2.1.1 History of Systems Engineering as a Discipline

Systems engineering is a young discipline in comparison to other engineering fields. The concepts of systems engineering were first used in the early 1900s in Bell Laboratories from which the term “systems engineering” arose. In 1950 it was first taught in a university environment at MIT by the laboratory’s Director of Systems Engineering [2]. The concepts were later adopted by the Department of Defense during World War II with the development of missiles and missile-defense systems [11]. Also during that time, the RAND Corporation created the concept of systems analysis and the term functional allocation was defined [4]. The first book on systems engineering was written by Goode and Machol in 1957 titled “System Engineering – An Introduction to the Design of Large-Scale Systems [4], [11].

As this new concept began to develop and be adopted by organizations, various handbooks on systems engineering were written [12]-[15]. The first military/government document written was in 1966 and additional documents written each subsequent decade. The first industry document on systems engineering was written in 1989 by the Institute of Electrical and Electronics Engineers

(IEEE) and later the National Astronautics and Space Administration (NASA) in 1995 [16]. The discipline's professional society, the International Council on Systems Engineering (INCOSE), was founded a few decades ago in 1990. As other engineering disciplines began to realize the value of systems engineering, engineering societies created systems engineering divisions, such as IEEE, The American Institute of Aeronautics and Astronautics (AIAA) and the American Society for Engineering Education (ASEE), and National Defense Industrial Association (NDIA). ASEE established a Systems Engineering Constituent Committee (SECC) in 2002. A myriad of activities are occurring aimed to build and define the profession of systems engineering.

An effort to define a common, universal set of knowledge areas and topics of systems engineering began in 2009 under the title: the Body of Knowledge and Curriculum to Advance Systems Engineering (BKCASE) [17], [18]. This project worked to develop two products: the Systems Engineering Body of Knowledge (SEBoK) and the Graduate Reference Curriculum for Systems Engineering (GRCSE ™) [19], [20]. Contributing authors were from the following organizations: The INCOSE, the IEEE Computer Society, the IEEE Systems Council, the Institute of Industrial Engineers (IIE) and the NDIA Systems Engineering Division. Industry involvement is international and widespread. The first versions of each were released in 2012. SEBoK is updated annually, with version 1.9 released in July 2018, and GRCSE ™ version 1.1 was released in 2015.

2.1.1.1 Systems Engineering Definitions

To demonstrate the varied views of systems engineering, various definitions are presented in this section.

In 1962 Hall defined systems engineering as a function with five phases: (1) system studies or program planning; (2) exploratory planning, which includes problem definition, selecting objectives, systems synthesis, systems analysis, selecting the best system, and communicating the results; (3) development planning, which repeats phase 2 in more detail; (4) studies during development, which includes the development of parts of the system and the integration and testing of these parts; and (5) current engineering, which is what takes place while the system is operational and being refined [21]. This is a thorough definition aligning with the development and operational phases of a system, also known as a system's lifecycle. It includes many aspects of systems engineering that still hold true today. Note the use of the word "function".

"Systems engineering is the design, and successful implementation of processes which will manage the design, development and maintenance of complex, multidisciplinary entities." [22]

Encyclopedia Britannica states "Systems engineering is the technique of using knowledge from various branches of engineering and science to introduce technological innovations into the planning and development stages of a system [23]. "This definition is incomplete and can be misleading.

New World Encyclopedia states "Systems engineering is an interdisciplinary field of engineering that focuses on how complex engineering projects should be designed and managed [24]. " This is a very concise definition.

Fabrycky has written textbooks and articles on systems engineering and states “Systems engineering may be described as a technologically based interdisciplinary process for bringing human-made systems and their products (technical entities) into being.”[1] Note the use of the word “process”. This definition does not explicitly include system transition to operation.

The Systems Engineering process involves the use of appropriate technologies and management principles in a synergetic manner. Its application requires synthesis and a focus on process, along with a new thought process to meet 21st Century challenges [25]. The word “process” is used again.

INCOSE states “Systems engineering is an overarching discipline, providing the tradeoffs and integration between system elements to achieve the best overall product and/or service. Although there are some important aspects of project management in the systems engineering process, it is still much more of an engineering discipline than a management discipline. It is a very quantitative discipline, involving tradeoff, optimization, selection, and integration of the products of many engineering disciplines.”[14] This definition includes the terms integration, tradeoffs, and selection and refers to “the systems engineering *process*”. The focus here is more on aspects of systems engineering as an engineering discipline rather than as a process.

Each definition includes aspects of systems engineering or a very high level statement. Common threads in these definitions include the ideas that systems engineering is a process, that it is involved in the design and development of a system (or product), and that it is interdisciplinary (including management). Some definitions mention analysis, tradeoffs, selection and integration.

From these, the following definition is offered: Systems engineering as a discipline is a way of thinking about systems, understanding and capturing their complexities, and enabling their optimal realization. Systems engineering also provides processes and toolsets used to define, analyze, design, implement, operate and dispose of a system.

2.1.2 The World of Systems

In order to better understand the ambiguous and differing definitions of systems engineering, it may be helpful to step backward and upward and look at the definition of a system and various applied terms. The basic idea of a system can be defined as:

(1) A set of elements in interaction [26].

(2) A combination of interacting elements organized to achieve one or more stated purposes [27].

There are abstract systems and concrete systems, open systems and closed systems. All systems have a boundary. The International Council on Systems Engineering Handbook (INCOSE) defines a system as “an interacting combination of elements to accomplish a defined objective”. An engineered system is created by and for people, having a purpose and satisfying key stakeholders’ value propositions when considered as part of a broader system context [28]. Knowing what a system is and being able to define it then leads to the study of a system, how to think about a system and how to engineer a system. This is guided by the following terms.

Systems Approach is defined as a set of principles for applying systems thinking to engineered system contexts [29]. Jackson et al. describes its application to engineered systems as “a comprehensive problem identification and resolution approach based upon the principles, concepts, and tools of systems thinking and systems science, along with the concepts inherent in engineering problem-solving. It incorporates a holistic systems view that covers the larger context of the system, including engineering and operational environments, stakeholders, and the entire life cycle."[30]

Systems Thinking is the integrating paradigm for systems science and systems approaches to practice [31].

Systems Science is an interdisciplinary field of science that studies the nature of complex systems in nature, society, and engineering [32].

Both of these terms, systems science and systems thinking, are part of a wider systems knowledge that make practical systems concepts, principles, patterns and tools accessible to systems engineering. This background knowledge of systems lays the foundation of systems engineering enabling the realization of successful systems [33].

2.1.3 Emergence of Systems Engineering

Systems engineering has formalized into a field of its own, and its methods are applied in various industries and applications. Increased efforts have been made to address how to prepare the engineering workforce to utilize knowledge from this field. The workforce includes current, working engineers and future engineers that will enter the workforce.

2.1.3.1 Industry

Industry and government recognize the need to define and educate its workforce in systems engineering. As mentioned previously, handbooks have been written and a body of knowledge established as a means to create a universal language and definition of systems and systems engineering that can be followed. Organizations have produced guidelines and documentation identifying desired systems engineering competencies of their workforce [12], [34]. In 2009, Squires, et. al. published a paper describing a method to map an organization's system engineering capabilities to a set of government-industry defined systems engineering needs [35]. The result provides an approach to identify competency gaps in employees and areas of improvement in training programs. At the discipline level, engineers can demonstrate their competencies through attainment of a Systems Engineering Professional Certification administered by INCOSE.

Discussions also extend to the preparations of college graduates for career readiness in systems thinking and systems engineering. One of the largest formal systems engineering programs (at the graduate level) was established as early as the 1980s from the realization by a former research lab director that on-the-job training of systems engineers was not the best approach. "There was a clear need in government and other large defense contractors for more and better-qualified systems engineering to address increasingly complex problems in both the commercial and the military domains" [1]. Presentations, panel discussions and workshops on what to include and how to include systems engineering in higher education are held at conferences across the world in the IEEE society and ASEE Systems Engineering Division workshops [1], [4]-[9], [36]-[42] .

An organization facilitating meeting industry's needs for systems-competent engineering graduates is the Systems Engineering Research Center (SERC) which was founded in 2008. It is comprised of systems engineering researchers from 22 collaborator universities with a mission to develop partnerships between academia, government, and industry with a focus on solving systems challenges that are critical to U.S. national security through systems research [43]. SERC organizes a Capstone Marketplace which connects senior engineering students at participating universities with problems to be solved for government agencies.

2.1.3.2 Academic Programs

With the recognized need for increased knowledge of systems engineering, the engineering community began to look towards academia to educate its future engineers. Systems engineering education can take one of two approaches: domain-centric or systems-centric. Domain-centric is incorporating systems engineering into a specific domain, such as an existing engineering degree program. Systems-centric is creating a systems engineering specific degree program [44].

A large growth in programs occurred between the year 2000 and 2010. In 2005, there were 31 US institutions offering 48 systems centric degree programs in systems engineering (11 bachelor programs) and 48 institutions offering 82 domain centric systems engineering degree programs (32 bachelor programs). However, none of the domain centric programs found were in mechanical engineering [44]. In 2009 there were 56 systems centric programs (an increase of 8 at the graduate level only) and 109 domain centric programs with 44 at the bachelor level [1].

This increase in systems engineering academic programs gave rise to a variety of educational approaches. Fabrycky explored these differences at the 2005 INCOSE International Symposium by evaluating and comparing systems engineering degree programs offered in the United States [44]. The need for universal guidance and an approach to systems engineering education was needed. In 2012 the Graduate Reference Curriculum for Systems Engineering (GRCSE ™) was released to provide guidance and curricular elements for the development of a systems-centric systems engineering master's degree program [45]. As a means to facilitate future students of systems engineering in finding degree programs, the Worldwide Directory of Systems Engineering and Industrial Engineering Programs was created in 2015 and is updated annually. The directory includes programs at the graduate, undergraduate and certificate level [46].

No formal guidance for systems engineering programs is given at the undergraduate level. However, the engineering education field continues to discuss how to integrate systems engineering and systems thinking into undergraduate courses and curricula [37], [47]-[54]. Mainly, institutions describe how they incorporate systems engineering into a specific course or project. ASEE conducted a systems engineering division workshop and panel at the 2017 and 2018 annual conferences. The focus of these workshops and panels is on ways of incorporating systems engineering into the undergraduate engineering education [55]. Attendees are comprised of educators from institutions across the United States. Discussions focus on first year and capstone courses and the importance of systems engineering in transforming education. Workshop content is discussed further in the analysis chapter. At the 2016 IEEE Frontiers in Education Conference, a panel of systems engineering educators discussed the importance of, and challenges of, including systems engineering in the undergraduate education. They also shared best practices [47].

Another way the importance of systems thinking and systems engineering in education is recognized is through the addition of systems language in the ABET accreditation changes for the 2019-2010 cycle [56]. In particular, the definitions section adds the following systems engineering related definitions: Complex Engineering Problems, Engineering Design and Team. These new definitions can be found in Table 1. The previous criteria lacked language on complexity. This addition demonstrates the awareness of increasingly complex engineered systems and inherently the need for a systematic and methodical approach to solve these complex problems. The Engineering Design definition draws from the previous criterion 3 and 5, but adds additional language from the systems engineering discipline. Specifically to the process of engineering design as a way to "meet desired needs", the addition of "and specifications within constraints" was added. Additionally, engineering design is defined to include not only concept/solution generation but also decision making and risk analysis. Examples of design constraints are listed and include several "-ilities" from systems engineering. These are highlighted in bold in Table 1. Including Team in the definitions serves to emphasize the reality that engineers will be working with others possessing differing skills and education. Systems engineering is about multidisciplinary teams working together for a common outcome, utilizing people of different disciplines, backgrounds, and specialties, facilitating communication with each other and drawing coherency among all to produce a product.

Table 2 highlights systems engineering language in Criterion 3. Specifically, in student outcome #1, the word "complex" is added to "engineering problems" to highlight, again, that these engineering problems are becoming more complex and an approach to solve this complexity is needed.

Table 1: New ABET Definitions for AY2019

Complex Engineering Problems	Complex engineering problems include one or more of the following characteristics: involving wide ranging or conflicting technical issues, having no obvious solution, addressing problems not encompassed by current standards and codes, involving diverse groups of stakeholders, including **many component parts or sub-problems**, involving **multiple disciplines**, or having significant consequences in a range of contexts.
Engineering Design	Engineering design is a process of devising a system, component, or process to meet desired needs and **specifications** within constraints. It is an iterative, creative, decision making process in which the basic sciences, mathematics, and engineering sciences are applied to convert resources into solutions. **Engineering design involves identifying opportunities, developing requirements, performing analysis and synthesis, generating multiple solutions, evaluating solutions against requirements, considering risks, and making trade-offs, for the purpose of obtaining a high-quality solution under the given circumstances.** For illustrative purposes only, examples of possible constraints include accessibility, aesthetics, codes, constructability, cost, **ergonomics,** extensibility, functionality, **interoperability,** legal considerations, **maintainability, manufacturability,** marketability, policy, regulations, schedule, standards, **sustainability,** or **usability.**
Team	A team consists of more than one person working toward a common goal and should include individuals of **diverse backgrounds, skills**, or perspectives.

Table 2: New Systems Language in ABET Criterion 3

Criterion 3 - Student Outcomes	
Previous Language	New Language
(a) an ability to apply knowledge of mathematics, science, and engineering (e) an ability to identify, formulate, and solve engineering problems	1. an ability to identify, formulate, and solve **complex** engineering problems by applying principles of engineering, science, and mathematics
(c) an ability to design a system, component, or process to meet desired needs within realistic constraints such as economic, environmental, social, political, ethical, health and safety, manufacturability, and sustainability	2. an ability to apply **engineering design** to produce solutions that meet **specified** needs with consideration of public health, safety, and welfare, as well as global, cultural, social, environmental, and economic factors

2.1.4 Systems Engineering in Mechanical Engineering Curricula

Upon review of the aforementioned directory of systems engineering programs, none are found related to mechanical engineering. An internet search of mechanical engineering centric systems engineering programs is conducted; however, none are found by title. (search conducted 10/2/2017) A systematic literature review in search for publications on the topic of systems engineering in mechanical engineering curricula provides no relevant articles. The following search terms are used: ('systems thinking' or 'systems engineering') and 'mechanical engineering'. A second search is conducted using the following terms: ('systems thinking' or 'systems approach') and 'curricul*' and 'mechanical engineering'. The following databases are searched: ERIC EBSCO, SCOPUS, IEEE Frontiers in Education Conference Proceedings, ASEE Conference Proceedings and publications. A general search of "systems engineering" in IEEE Frontiers in Education Conference Proceedings, ASEE Conference Proceedings is conducted. One article is found regarding a program-level approach to systems engineering inclusion in "main stream engineering disciplines" but is specific to electrical engineering [57]. Another incorporates a systems approach to civil engineering [58]. Most articles found in engineering education publications present a specific way to introduce systems engineering in a particular course or with a particular project [36], [51], [59]. There is a general lack of research and investigations into a high-level curricular approach to systems engineering inclusion in undergraduate engineering disciplines and more specifically in mechanical engineering programs. There is no postulation on the reason for this.

3. METHODS

The investigation into the systems engineering competencies lacking in ME graduates is conducted through a mixed-methods, multi-step approach. First, a standard, industry-recognized set of competencies employed by systems engineers must be identified. Next, these skills are presented via a survey to graduates of mechanical engineering undergraduate programs to identify which of them are used in practice and which were not taught in their undergraduate ME education. A gap analysis is then conducted, comparing those competencies used in practice against ME curricula at major U.S. institutions. A final list of SE competencies used by MEs but not taught in the undergraduate program is generated. These are translated into program-level outcomes for incorporation into ME curriculum. Faculty feedback on these outcomes is garnered through interviews. All of this information is then used to develop methods of including needed concepts into a curriculum.

3.1 Competencies of a Systems Engineer

There currently is no single accepted systems engineering competency model that is globally applicable and accepted widely within the discipline of systems engineering. To the contrary, it is common practice for employers to establish a competency framework for their employees working in systems engineering-related roles that is tailored towards the organization’s business model, operating environment and project stakeholders [60]. The process of developing an organization's systems engineering competency model can be greatly informed and aided by evaluating the systems engineering competency models of other publicly available models. This approach is used here.

Several models to measure competencies in systems engineers have been developed by industry and academic institutions [61]. Despite this variation, the Systems Engineering Body of Knowledge (SEBoK) recognizes that all SE competency models include systems thinking, technical systems engineering methods and systems engineering managerial methods [20]. It also lists twelve systems engineering competency models developed by organizations for their specific use. Three models from this list are highlighted and explained: INCOSE UK WG Competency, DoD ENG Competency Model and NASA APPEL Competency Model. The United States Department of Defense (DoD) and the US National Aeronautics and Space Administration (NASA) are major employers of mechanical engineering graduates. These models appear more universal in their applicability of identified competencies than the other models listed. The INCOSE UK WG model was developed by a working group of employers from industry and government, as well as academia. This model is inherently universal and not tied to a particular organization or industry. By design, it has been created for general applicability to all systems engineering activities. For these reasons, these three competency models are used as a foundation for establishing a list of systems engineering competencies for the survey to mechanical engineering graduates. Each model is explained in more detail in the following subsections followed by the process of creating a final competency list for the survey.

3.1.1 The Department of Defense Competency Model

The DoD model, called the ENG Competency Model, was created in 2013 by the Defense Acquisition University (DAU) [62]. DAU offers courses and training to current employees. Other versions existed previously, however this version was created as part of a career field organizational realignment. The model is composed of 4 categories (analytical, technical, management, professional and business acumen) and a total of 41 competencies their engineering

Table 3: DoD--ENGE Competency Model

Analytical (11)	Professional (10)
1. Mission-Level Assessment	22. Problem Solving
2. Stakeholder Requirements Definition	23. Strategic Thinking
3. Requirements Analysis	24. Professional Ethics
4. Architecture Design	25. Leading High-Performance Teams
5. Implementation	26. Communication
6. Integration	27. Coaching and Mentoring
7. Verification	28. Managing Stakeholders
8. Validation	29. Mission and Results Focus
9. Transition	30. Personal Effectiveness/Peer Interaction
10. Design Considerations	31. Sound Judgment
11. Tools and Techniques	
Technical Management (10)	**Business Acumen (10)**
12. Decision Analysis	32. Industry Landscape
13. Technical Planning	33. Organization
14. Technical Assessment	34. Cost, Pricing, and Rates
15. Configuration Management	35. Cost Estimating
16. Requirements Management	36. Financial Reporting and Metrics
17. Risk Management	37. Business Strategy
18. Data Management	38. Capture Planning and Proposal Process
19. Interface Management	39. Supplier Management
20. Software Engineering	40. Industry Motivation, Incentives, Rewards
21. Acquisition	41. Negotiations

acquisition employees should possess. These are listed in Table 3. Definitions are shown in the in the subsection “Establishing a Final List”. The model is predominantly used by organizations within the DoD to create career milestones and includes general professional, engineering skills as well as systems-engineering specific competencies. The systems engineering competencies will be used to inform the survey. This process is explained further in a subsequent section.

3.1.2 NASA APPEL Competency Model

The NASA model was created by the Academy of Program/Project & Engineering Leadership (APPEL) Knowledge Services in 2009 to guide and train their technical workforce [63]. APPEL Knowledge Services offers training and courses to current employees. This model is composed of both a systems engineering and project management competency model, with overlapping competencies identified in a shared competency model. For the purposes of this study, only the systems engineering competency model is used. It contains three sections (system design, product realization and technical management) and 17 competencies which can be found in Table 4. Definitions are shown in the in the subsection "Establishing a Final List".

Table 4: NASA APPEL Model

System Design (4)
SE 1.1 - Stakeholder Expectation Definition & Management
SE 1.2 - Technical Requirements Definition
SE 1.3 - Logical Decomposition
SE 1.4 - Design Solution Definition
Product Realization (5)
SE 2.1 - Product Implementation
SE 2.2 - Product Integration
SE 2.3 - Product Verification
SE 2.4 - Product Validation
SE 2.5 - Product Transition
Technical Management (8)
SE 3.1 - Technical Planning
SE 3.2 - Requirements Management
SE 3.3 - Interface Management
SE 3.4 - Technical Risk Management
SE 3.5 - Configuration Management
SE 3.6 - Technical Data Management
SE 3.7 - Technical Assessment
SE 3.8 - Technical Decision Analysis

3.1.3 INCOSE UK Competency Model

The International Council of Systems Engineering (INCOSE) model was developed out of a working group in the United Kingdom (UK) chapter [60]. The United Kingdom Advisory Board (UKAB), composed of industry, academia and government organizations of the UK, created the Systems Engineering Competencies Framework, originally in 2006 with an update in 2010. The objective of this document is to provide definitions and guidance to both employers and employees as to the levels of skills required to conduct "good" systems engineering. It consists of three areas (systems thinking, systems engineering management and holistic lifecycle view) and a total of 21 competencies with corresponding knowledge indicators to be used for employee/team assessment.

This is the most detailed model of the three used in this study. A list of competencies can be found in Table 5. Definitions are shown in the in the subsection "Establishing a Final List".

Table 5: INCOSE Framework

Systems Thinking
1. System Concepts
2. Super-System Capability Issues
3. Enterprise and Technology Environment
Systems Engineering Management
1. Concurrent Engineering
2. Enterprise Integration
3. Integration of Specialties
4. Lifecycle Process Definition
5. Planning, Monitoring, and Controlling
Holistic Lifecycle View
1. Determining and Managing Stakeholder Requirements
2. Systems Design
a. Architectural Design
b. Concept Generation
c. Design For...
d. Functional Analysis
e. Interface Management
f. Maintain Design Integrity
g. Modeling and Simulation
h. Select Preferred Solution
i. System Robustness
3. Systems Integration & Verification
4. Validation
5. Transition to Operation

3.1.4 Model Comparisons / Establishing a Final List

A comparison of all three models is made in order to establish a converging list of systems engineering competencies that are widely recognized as needed in the workplace to manage complex systems. First, the competencies from all three models are grouped into the overarching areas of systems thinking, system life cycle, and systems management. These areas mirror the INCOSE framework which is chosen because of its universality as a professional society and focus on systems engineering competencies. Next, those competencies relating strictly to general professional skills or project management are eliminated. These can be found in Table 8 and have a strikethrough. Then, redundant competencies and those deemed too detailed and specific to a Systems Engineer role (based on literature review) are eliminated, and similar competencies are combined and renamed. Related skills and competencies can be found in Table 7 and Table 8, and associated cells are highlighted in gray.

Table 6 shows competencies from the three models that fall within the area of systems thinking. These include broad systems concepts, the idea of a system of systems (or subsystems) and the context of the system within its environment. Only the INCOSE model has related competencies. The following competencies are found in the Management area of the INCOSE model but are included in the Systems Thinking area of the newly created list: Enterprise Integration (considerations of the system operating within other functional areas, i.e. marketing, quality assurance) and Integration of Specialties (utilizing appropriate subject matter experts). These are more related to systems thinking and a systems approach (how a person views a system and its context) than management processes (procedures to organize tasks).

**Table 6: Systems Thinking Area-
Related Competencies from the Three Identified SE Models**

Systems Thinking		
INCOSE Model	**DoD Model**	**NASA Model**
System Concepts	(N/A)	(N/A)
Super-System Capability Issues		
Enterprise and Technology Environment		
Enterprise Integration		
Integration of Specialties		

Table 7 shows competencies from the three models that fall within the area of system life cycle. System life cycle refers to the stages of a system, from concept to operation to disposal (end of system). Competencies in this area are associated with one of the system stages. For the purposes of this study, the specific stages are not relevant and will not be discussed further. Related competencies from each model are grouped in the same row. Those cells highlighted in gray identify competencies among the three models that are similar enough to be merged into one competency for the final list.

Lifecycle process definition was moved from the management area of the INCOSE model to the Lifecycle area of the new list for direct alignment. The INCOSE model considers this a management competency because it defines the phases of the system which influences the planning and overall management of the system. From a definition and understanding viewpoint, the competency of defining a system lifecycle process belongs in the Lifecycle area. Architecture Design (INCOSE, DOD) is defining the system architecture (or levels) and associated derived

Table 7: Life Cycle Area- Related Competencies from the Three Identified SE Models

Lifecycle		
DoD Model	**NASA Model**	**INCOSE Model**
1. Mission-Level Assessment	SE 1.3 - Logical Decomposition	System Robustness
2. Stakeholder Requirements Definition	SE 1.1 - Stakeholder Expectation Definition & Management	Determining and Managing Stakeholder Requirements
3. Requirements Analysis	SE 1.2 - Technical Requirements Definition	Design
4. Architecture Design	SE 1.4 - Design Solution Definition	Architecture Design
5. Implementation	SE 2.1 - Product Implementation	Concept Generation
6. Integration	SE 2.2 - Product Integration	Interface Management
7. Verification	SE 2.3 - Product Verification	Functional Analysis
8. Validation	SE 2.4 - Product Validation	Maintain Design Integrity
9. Transition	SE 2.5 - Product Transition	Select Preferred Solution
10. Design Considerations		Design For...
11. Tools and Techniques		Modeling and Simulation
		Lifecycle Process Definition
		Systems Integration & Verification
		Validation
		Transition to Operation

requirements. This is included in NASA’s Logical Decomposition. The requirements part of this competency is assumed to be captured in Requirements Analysis, and the system definition part captured through Modeling and Simulation. NASA’s Technical Requirements Definition is re-worded to Technical Specifications since these are written as quantifiable and measurable descriptions. Design Solution Definition is NASA’s version of INCOSE’s Concept Generation and Select Preferred Solution. It also includes the Decision Analysis process, included in the management area of the DOD and NASA models. Decision Analysis/Evaluate Solutions is created for the lifecycle area in the final list to represent the competency of evaluating solution alternatives to make a final selection during the design phase of a system lifecycle. Concept Generation is also included, and Design Solution Definition is removed. Maintain Design Integrity was removed since this involves ensuring the system retains its original intent and meets stakeholder requirements. This is assumed to be included in Stakeholder Requirements Definition, Requirements Analysis and System Verification and Validation. Design Considerations (DOD) and Design For (INCOSE) are combined into Design Considerations for the "-ilities". This competency includes additional considerations to consider in the design process that are outside of the stakeholder requirements and functions to be performed by the system. Most of these end in “-ility” and so in the systems engineering world, they are commonly called the “-ilities”. System Implementation (DOD, NASA) is renamed System Realization to better represent its definition of the process of bringing the system elements into existence. Implementation, to those unfamiliar, may be interpreted at a glance as referring to an existing system element being implemented (integrated) into the overall system or operating environment. Interface Management is included in the Lifecycle Area of the INCOSE model and in the Management Areas of the DOD and NASA models. The purpose of inclusion in this area is the process of defining interfaces where system elements interact to inform design constraints and requirements. Thus the concept is renamed to Interface Requirements for the Lifecycle Area. Interface Management remains in the Management Area.

Table 8 shows competencies from the three models that fall within the area of systems management which includes competencies related to the planning, documenting and oversight of a system. Related competencies from each model are grouped in the same row where feasible. Interface Management from the Lifecycle area of the INCOSE model is included in this area to align with the other two models. In this area the focus is on managing the complexity of interfaces within the system and beyond the system. The DOD model includes many competencies in the categories of business acumen, professionalism and technical management. For conciseness of space in the table, these competencies flow into columns two and three and are separated by a bold line. Most of these knowledge areas are not related to systems engineering and have a strikethrough. They will not be included in the final list for the survey. Those cells highlighted in gray identify competencies among the three models that are similar enough to be considered overlapping and equivalent. They can be combined into one for the final list.

Table 8: Management Area- Related Competencies from the Three Identified SE Models

Management		
DoD Model	**NASA Model**	**INCOSE Model**
12. Decision Analysis	SE 3.8 - Technical Decision Analysis	Concurrent Engineering
13. Technical Planning	SE 3.1 - Technical Planning	Planning, Monitoring, and Controlling
14. Technical Assessment	SE 3.7 - Technical Assessment	
15. Configuration Management	SE 3.5 - Configuration Management	
16. Requirements Management	SE 3.2 - Requirements Management	
17. Risk Management	SE 3.4 - Technical Risk Management	
18. Data Management	SE 3.6 - Technical Data Management	
19. Interface Management	SE 3.3 - Interface Management	Interface Management
28. Managing Stakeholders	SE 1.1 - Stakeholder Expectation Definition & Management	Determining and Managing Stakeholder Requirements
~~20. Software Engineering~~	~~30. Personal Effectiveness/Peer Interaction~~	39. Supplier Management
21. Acquisition	~~31. Sound Judgment~~	~~40. Industry Motivation, Incentives, Rewards~~
~~22. Problem Solving~~	~~32. Industry Landscape~~	~~41. Negotiations~~
~~23. Strategic Thinking~~	~~33. Organization~~	
~~24. Professional Ethics~~	~~34. Cost, Pricing, and Rates~~	
25. ~~Leading High-Performance Teams~~	~~35. Cost Estimating~~	
~~26. Communication~~	~~36. Financial Reporting and Metrics~~	
~~27. Coaching and Mentoring~~	~~37. Business Strategy~~	
29. Mission and Results Focus	~~38. Capture Planning and Proposal Process~~	

From these lists, a new and final list of competencies is made. Those similar competencies highlighted in gray are combined into one. Those unrelated to systems engineering, with a strikethrough, are removed. A change in groupings is also made due to the large number of competencies in the Lifecycle area. For simplicity and easier comprehension of the competencies in a survey format, this area is broken into to two sub-areas: Design and Implementation. Most of the lifecycle competencies can be grouped into one of these two major phases in a system life cycle. The final list of competencies and groupings generated are shown in the tables below: Table 9: Systems Thinking, Table 10: System Lifecycle—Design, Table 11: System Lifecycle—Implementation, Table 12: System Management.

Table 9: Systems Thinking Area Competency Definitions

COMPETENCY	DEFINITION	SOURCE
System Concepts	Understanding what a system is, its context within its environment, its boundaries and interfaces, and that it has a lifecycle.	INCOSE
System of Systems	An appreciation of the role the system plays in the overall system of which it is a part.	INCOSE
Enterprise And Technology Environment	The definition, development and production of systems within an enterprise and technological environment.	INCOSE
Enterprise Integration	Acknowledgement of and coordination with other functions within an enterprise, such as marketing, sales, and human resources.	INCOSE
Integration of Specialties	Effective inclusion and coordination of specialists in the areas of reliability, maintainability, testability, integrated logistics support, producibility, electromagnetic compatibility, human factors and safety.	INCOSE

Table 10: System Lifecycle—Design Area Competency Definitions

COMPETENCY	DEFINITION	SOURCE
Stakeholder Expectation Definition	To identify the stakeholder needs and expectations for a system.	INCOSE DOD NASA
Requirements Analysis	Transforming needs into testable and traceable requirements.	DOD NASA
Functional Analysis	Used to determine which functions are required by the system to meet the requirements.	INCOSE
Technical Specifications	Defining requirements with quantitative and measurable descriptions.	NASA
Interface Requirements	Identification, definition and control of interactions across system or system element boundaries.	INCOSE
Concept Generation	Generation of potential system solutions that meet a set of needs.	INCOSE DOD NASA
Decision Analysis/Evaluate Solutions	Select preferred solution through a formal decision making process.	INCOSE DOD NASA
Modeling And Simulation	Modeling is a physical, mathematical or logical representation of a system entity, phenomenon or process. Simulation is the implementation of a model over time. A simulation brings a model to life and shows how a particular object or phenomenon will behave.	INCOSE DOD
System Robustness	A robust system is tolerant of misuse, out of spec scenarios, component failure, environmental stress and evolving needs.	INCOSE
Design Considerations for the "-ilities"	Ensure requirements for later lifecycle stages are addressed. Consideration should be given to manufactura*bility*, testab*ility*, reliab*ility*, maintainab*ility*, safety, security, flexib*ility*, interoperab*ility*, capab*ility* growth and disposal.	INCOSE DOD

Table 11: System Lifecycle—Implementation Area Competency Definitions

COMPETENCY	DEFINITION	SOURCE
System Realization	All activities to make the design become reality (fabrication, construction, programming).	DOD NASA
System Integration	A logical process for assembling the system into a functional unit.	INCOSE DOD NASA
System Verification	Checking the system against design requirements.	INCOSE DOD NASA
System Validation	Checking the system against customer needs.	INCOSE DOD NASA
Transition to Operation	Transit of the system to its operational environment (integration into system of systems). Includes provision of support activities: site preparation, training, logistics.	INCOSE DOD NASA

Table 12: System Management Area Competency Definitions

COMPETENCY	DEFINITION	SOURCE
Decision Analysis	Evaluating technical decision issues, identifying and analyzing alternatives and communicating findings.	DOD NASA
Technical Planning	Planning the technical effort needed and management of technical processes.	DOD NASA
Technical Assessment	Monitoring progress of technical effort and supporting system design, product realization and technical management through technical status information.	DOD NASA
Configuration Management	Documenting and controlling changes to product or system configuration.	DOD NASA
Requirements Management	Using formal requirements management procedures and tools to conduct requirements traceability audits to track, control and communicate changes to requirements.	DOD NASA
Risk Management	Identifying, monitoring, and assessing risks and developing mitigation plans.	DOD NASA
Data Management	Using formal processes to acquire, assess, distribute, control and dispose product-related data throughout the lifecycle.	DOD NASA
Interface Management	Using formal interface management procedures and documentation to maintain interface definitions and compliance.	INCOSE DOD NASA
Acquisition	Applying knowledge of laws, regulations, policies, processes and procedures related to the lifecycle management activities needed to acquire and sustain products and services.	DOD
Managing Stakeholders	Building and managing effective relationships with all stakeholders and collaborating across boundaries, finding common ground.	INCOSE DOD NASA
Concurrent Engineering	Managing and coordinating concurrent lifecycle activities and the parallel development of system elements.	INCOSE
Planning, Monitoring and Controlling	Establishing and maintaining a systems engineering plan which identifies systems engineering needs and coordination of systems engineering activities.	INCOSE
Mission and Results Focus	Aligns goals and work efforts toward fulfillment of the overall organizational mission.	DOD
Supplier Management	Applies knowledge of supply chain management to contribute to the preparation of acquisition strategies and solicitations, and to provide necessary technical oversight.	DOD

3.2 Survey of Mechanical Engineering Graduates

3.2.1 Survey Instrument

In order to validate the hypothesis that systems engineering concepts are needed by graduates of mechanical engineering programs, former students of such programs were surveyed. The survey asked the participant several questions regarding systems engineering competencies and captured demographic information pertaining to work history. A copy of the survey as distributed can be found in the appendix. Qualtrics was used to create, distribute and analyze the questionnaire form. Due to the nature of the survey being sent to human participants, a request for review of the study was submitted to the Internal Review Board (IRB). This research project was determined "not human research" and did not need a full review or approval by the IRB.

3.2.1.1 Survey Questions

After an introduction to the study, participants are asked a set of demographic-related questions in order to gather data on their career and work experience in relation to systems engineering. The following questions are asked.

Survey Demographic Questions

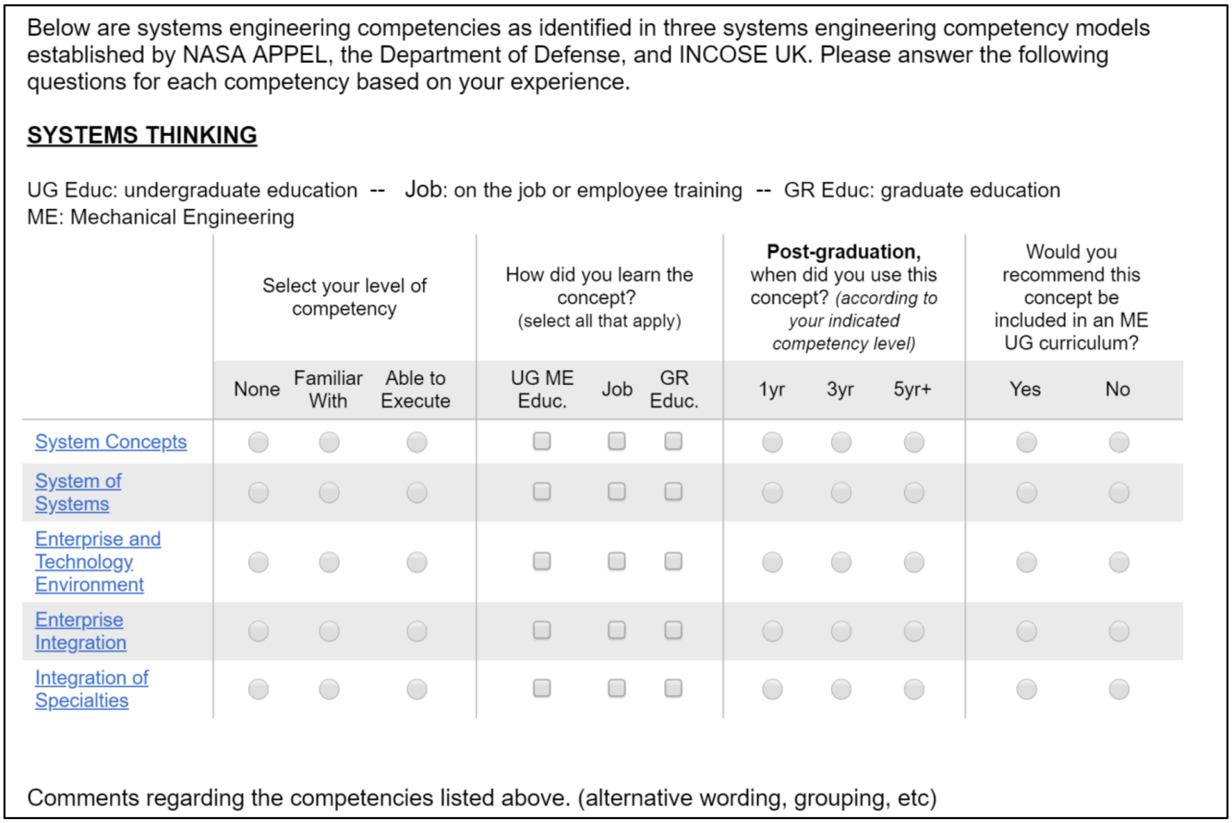
1. In what industry has the majority of your career been?
2. How many years of work experience do you have?
3. What is your current job title?
4. Have you ever performed in a Systems Engineer role?
5. Do you have formal training or education in systems engineering?
    a. If yes, what type of training?
        i. University degree (undergraduate or graduate)
        ii. Certificate or minor (college or professional)

iii. Employer Training Program
iv. Other

Following these questions, participants are given the option to submit the survey without continuing if they have not worked as a practicing engineer or have not been exposed to systems engineering.

The core set of questions center around a list of 34 systems engineering competencies separated into four categories, defined in Table 9, Table 10, Table 11, and Table 12. The information sought regarding these competencies are: the level of knowledge required in practice, at what point after graduation is that knowledge used, how did the graduate learn that knowledge, and should that skill be taught in a mechanical engineering undergraduate degree program. Participants had the option to leave comments regarding the list of competencies and wording used. Additionally, at the end of the survey respondents can leave additional commentary regarding the use of systems engineering concepts by practicing mechanical engineers.

To measure the need of the competency, participants are asked to select their level of competency from: none, familiar with or able to execute. This may change throughout a career, therefore a clarifying question is asked: "According to your indicated level of competency, select when you used this concept: 1yr, 3yr or 5yr+ post-graduation." To capture if the respondent had learned this concept in school or on the job, they are asked to select (all that apply) how they learned the concept: undergraduate mechanical engineering education, job, graduate education. To glean feedback on the respondents' opinion on inclusion of this competency in the mechanical engineering undergraduate curriculum, they are asked if they would recommend including the competency: yes or no. An image of the survey is shown in Figure 1.



Below are systems engineering competencies as identified in three systems engineering competency models established by NASA APPEL, the Department of Defense, and INCOSE UK. Please answer the following questions for each competency based on your experience.

SYSTEMS THINKING

UG Educ: undergraduate education -- Job: on the job or employee training -- GR Educ: graduate education
ME: Mechanical Engineering

	Select your level of competency			How did you learn the concept? (select all that apply)			**Post-graduation,** when did you use this concept? *(according to your indicated competency level)*			Would you recommend this concept be included in an ME UG curriculum?	
	None	Familiar With	Able to Execute	UG ME Educ.	Job	GR Educ.	1yr	3yr	5yr+	Yes	No
System Concepts											
System of Systems											
Enterprise and Technology Environment											
Enterprise Integration											
Integration of Specialties											

Comments regarding the competencies listed above. (alternative wording, grouping, etc)

Figure 1: Survey Layout for Systems Thinking Area

3.3.1 Survey Participants

The objective is to gather data from graduates of mechanical engineering undergraduate programs. The survey was sent to 6,629 mechanical engineering graduates comprised of industry contacts by the research investigators as well as graduates of Texas A&M University--College Station from the years 1970-2015. Of those sent, 6,375 actually received the email invitation due to 248 bounced emails. An anonymous link to the survey was included for invitees to share with their colleagues.

Fifteen responses were captured through this method. No personally identifying information was asked of the participants. The survey software links survey responses to participant email addresses as part of the distribution and follow-up features. Participant IP addresses are also collected by the software. However, this information was not used as part of the survey response analysis.

3.4 Curricula Investigation

Existing undergraduate mechanical engineering programs are reviewed for inclusion of systems engineering and systems thinking topics. Programs are selected based upon their U.S. News and World Reports ranking and their profile: large, public institutions with high enrollment and large faculty size for mechanical engineering. Nationally recognized programs are assumed to produce high quality graduates and have relevant curricula to the field and industry needs. High-enrolled programs produce a large number of graduates working in industry; presumably curricula would align with industry needs. Both of these categories align with the institution from which the majority of survey participants graduated.

First, the mechanical engineering undergraduate program websites are reviewed for a listing of program outcomes or objectives that included verbiage related to systems thinking, systems approach or systems engineering. Next, the curricula are reviewed for course titles or descriptions relating to systems or systems engineering. Finally, a gap analysis is performed comparing needed systems engineering competencies identified from the survey to concepts included in existing undergraduate mechanical engineering degree programs. From here, approaches to curricular inclusion of missing concepts is presented. The process and results are explained in further detail in the analysis and discussion chapter.

4. RESULTS

4.1 Survey Results

4.1.1 Descriptive Statistics

Participants are asked to submit the survey regardless of their work experience. A total of 1250 responses are recorded which is 20% of the surveys delivered. Once opening the survey, the respondent is given the option to indicate that they have no professional engineering experience or exposure to systems engineering and immediately submit the survey. A total of 640 respondents, 51%, selected this option. Of these responses, 19% indicated they have not worked as a practicing engineer and 71% did not think they used systems engineering concepts in their professional role. 10% chose to add their own reason providing further explanation as to why they don't think they use systems engineering concepts in their job. The surveys were submitted anonymously with no personally identifiable information collected.

From the participant-entered job titles, 62 have "mechanical engineer" in their title, 318 have "engineer" in their title, and 194 have "manager" in their title (without "engineer"). Of those with "engineer" in their title, 16 also have "systems" in their title. The years of work experience of the respondents are grouped by significant stages in an engineer's career. The overall average years of experience of all respondents is 20.12, with a maximum of 54 years of work experience and a minimum of one year. Results are shown in Figure 2.

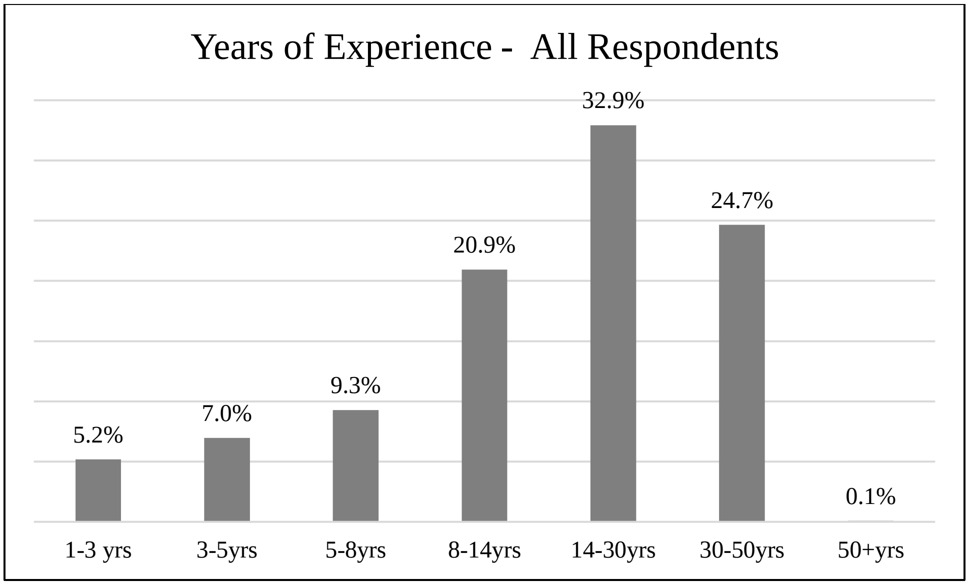


Figure 2: Participant Years of Work Experience

Industries reported by respondents are shown in Figure 3. Some responses included more than one industry. All were tallied; the most common industry is petroleum. There were 134 industries, or job areas, that had between one and nine responses. These make up less than 10% of responses and are grouped into a category titled “other”.

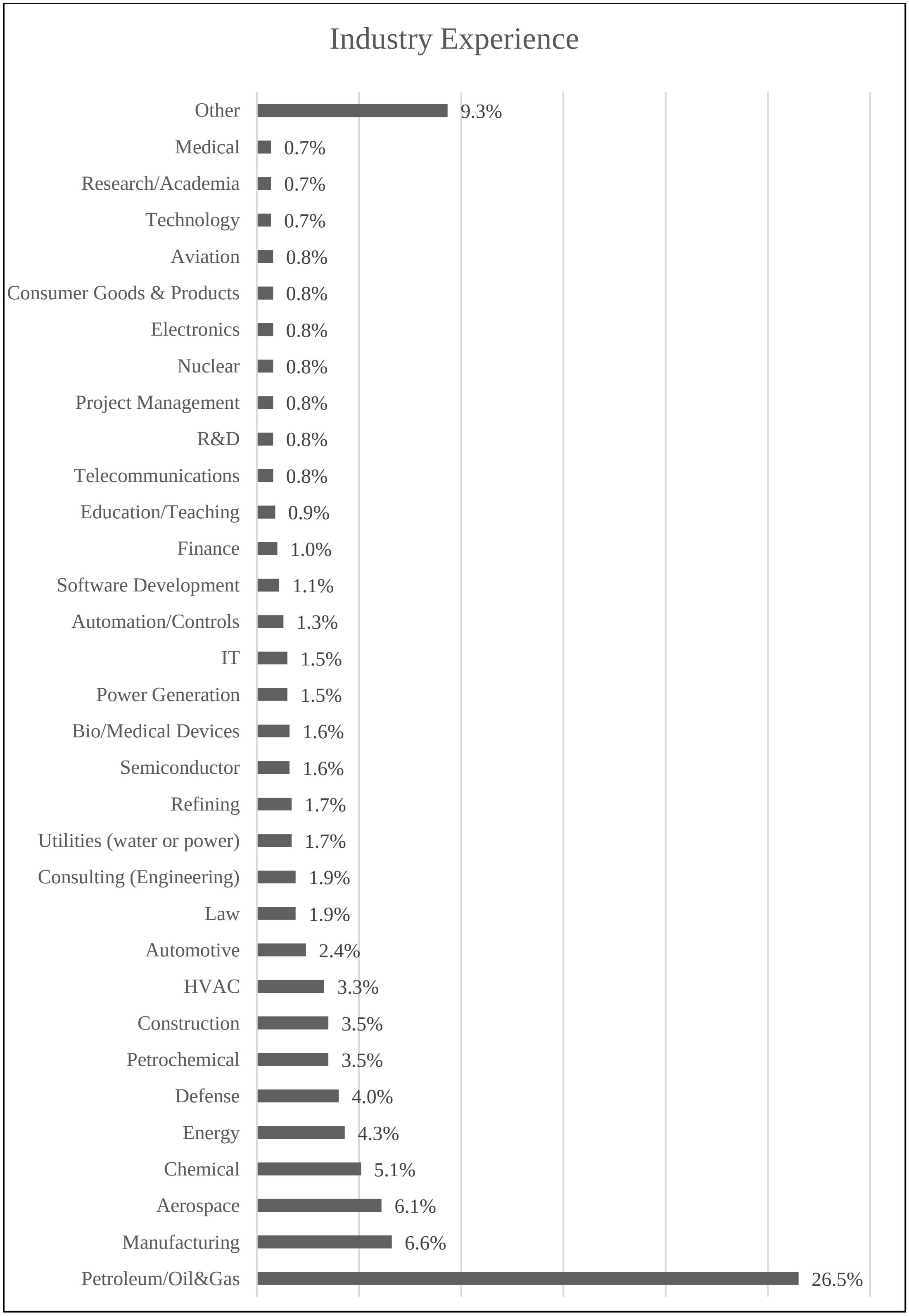


Figure 3: Participant Industries Worked

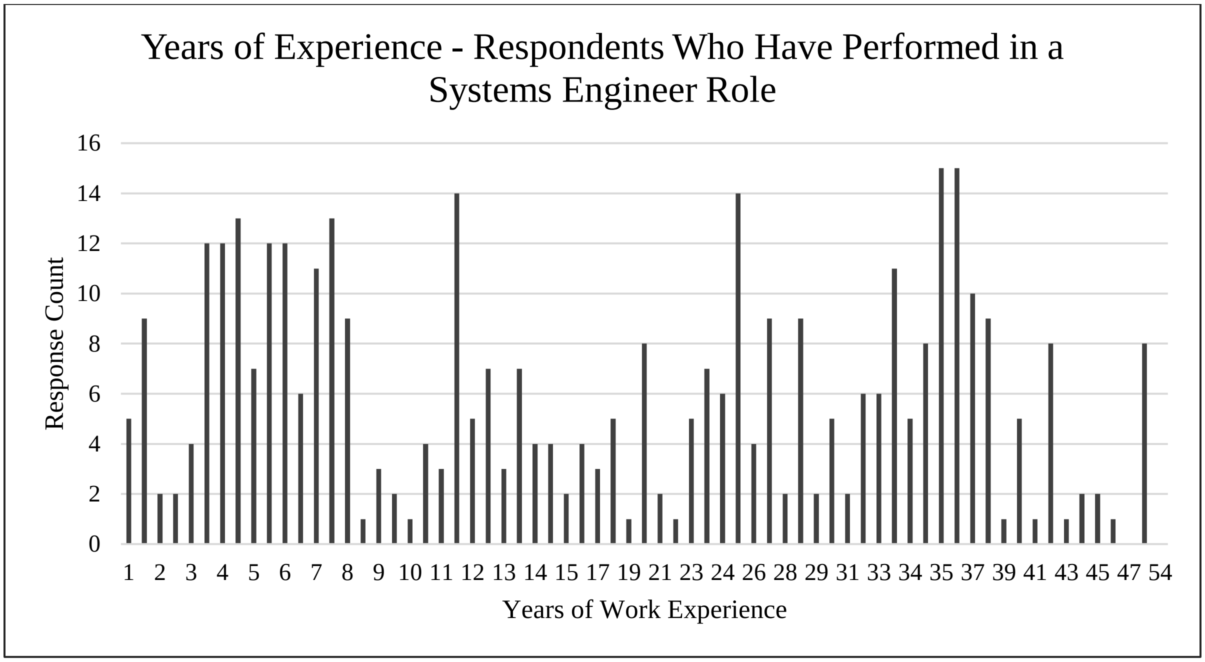


Figure 4: Years of Experience of Respondents Who Indicated They Have Performed in a Systems Engineer Role

Of the respondents, 31% indicate they have worked in a Systems Engineer role. The average number of years of post-graduation work experience of that grouping is 21.94. The remaining 69% who have not worked in such a role average 19.22 years of experience. A breakdown of total years of work experience since receiving the B.S. Mechanical Engineering for those who indicated they have performed in a systems engineer role is shown in Figure 4. The years of experience are shown as the participant indicated in the survey. Half-year increments were entered for years 1.5 through 13.5. Response counts are distributed widely and range from 0-15. Clusters of higher counts are in the 3-8 years of experience range and 35-39 years of experience range. In regards to industries, those that indicated they have performed in a systems engineer role have worked in almost all of the industries indicated in this survey. The top six industries with the most respondents who have performed in a systems engineer role (ranging from 11-25) are: petrochemical, defense, aerospace, energy and HVAC.

Of those that have worked in a Systems Engineer role, 33% have had formal training in systems engineering and 67% have not. A summary is shown in Table 13.

Table 13: Systems Engineer Role and Training

		Have you performed in a Systems Engineer role?		
		YES	**NO**	
Do you have formal training or education in systems engineering?	**YES**	129	259	**168**
	NO	39	818	**1077**
		388	**857**	**[1245]**

One hundred and sixty-eight respondents (13%) indicate they have had formal training in systems engineering. Those that had formal training are then asked what type of training. Three respondents in this category did not answer the follow-on question. Results are shown in

Table 14: 44% of training is from a university degree, 40% from employer-based training and 5% from a certificate or minor.

Table 14: Formal Systems Engineering Training

What type of training or education do you have?	University Degree	Certificate or Minor	Employer Training	Other
	72 *(44%)*	**9** *(5%)*	**66** *(40%)*	**18** *(11%)*

Some respondents, 4.5%, whom did not work in a Systems Engineer role still received formal training in systems engineering. Almost half, 46%, received training from a university degree. Several comments state that the respondent was exposed to some of these systems engineering competencies in their undergraduate curriculum. It is possible that respondents chose “University Degree” based upon their undergraduate mechanical engineering degree, not through a specific degree in systems engineering.

4.1.2 Survey Responses

As mentioned previously, all of the identified systems engineering competencies in question were grouped into four areas leading to sections of questions for the participants. Each section has both forced response and free response questions which are discussed in the following sections. Forced responses are presented as a percentage of submitted responses for each item. Some items are left unanswered within a section. The lowest responses are for the question “Post-graduation, when did you use this concept?” This is due to the lack of response choice “not used”. Therefore, if a respondent does not use the concept in their job, they would leave the answer blank. Multiple answers are allowed to the question, “How did you learn the concept”. However, only a few additional responses are counted beyond the response count for the first question, “Select your level of competency”. Using this question as a base question to compare response counts, a slight drop in answers is seen from the beginning to the end of the survey. Responses range from 431-452 in the first section and 316-368 in the last section. All participants should answer this question since “none” is a choice, but some items are unanswered. Overall, for each competency, the majority of respondents indicated it should be taught in an undergraduate mechanical engineering curriculum.

4.1.3 Section 1 Results- Systems Thinking

The first section is composed of high level systems engineering competencies grouped under the title "Systems Thinking". Participants are asked to indicate their level of competency for each, selecting from "none", "familiar with" or "able to execute". A summary of these results can be seen in Figure 5.

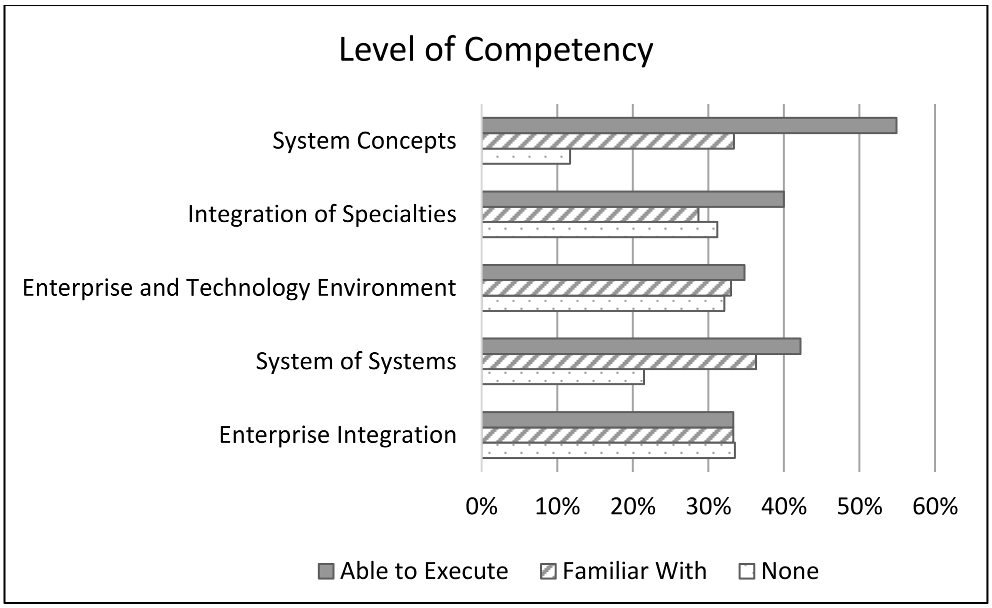


Figure 5: Systems Thinking Competency Level

Respondents are then asked to select how they learned this concept. They may select more than one from the following choices: undergraduate mechanical engineering education, on the job or through graduate education. Graduate education includes a certificate program as well as a masters or doctoral degree. Results are shown in Figure 6.

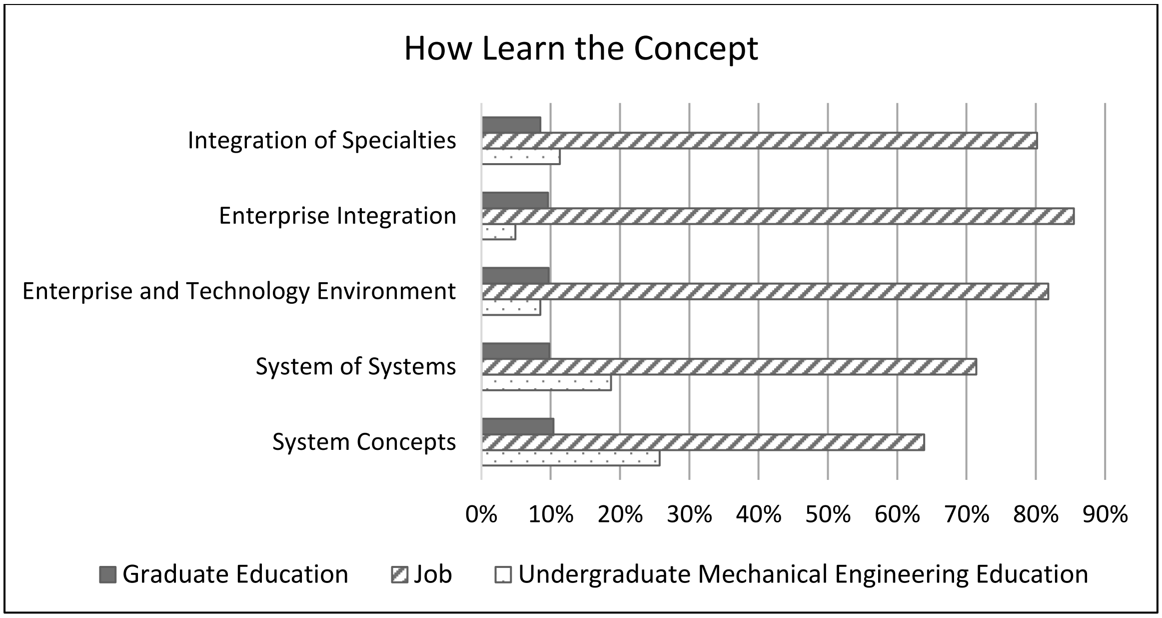


Figure 6: Systems Thinking How Learn Concept

Next, participants are asked if they would recommend this concept to be included in a mechanical engineering undergraduate curriculum. Choices are “yes” or “no”. Results are in Figure 7.

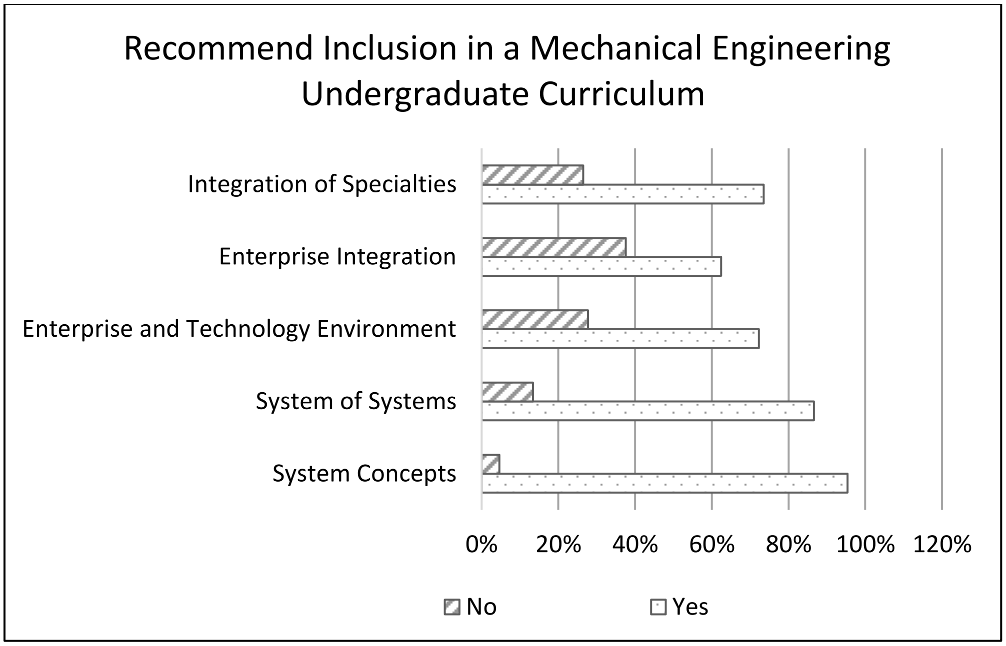


Figure 7: Systems Thinking Curricular Inclusion Recommendation

Finally, participants are asked at what point after their graduation with their BS in Mechanical Engineering they used each concept. Results are shown in Figure 8.

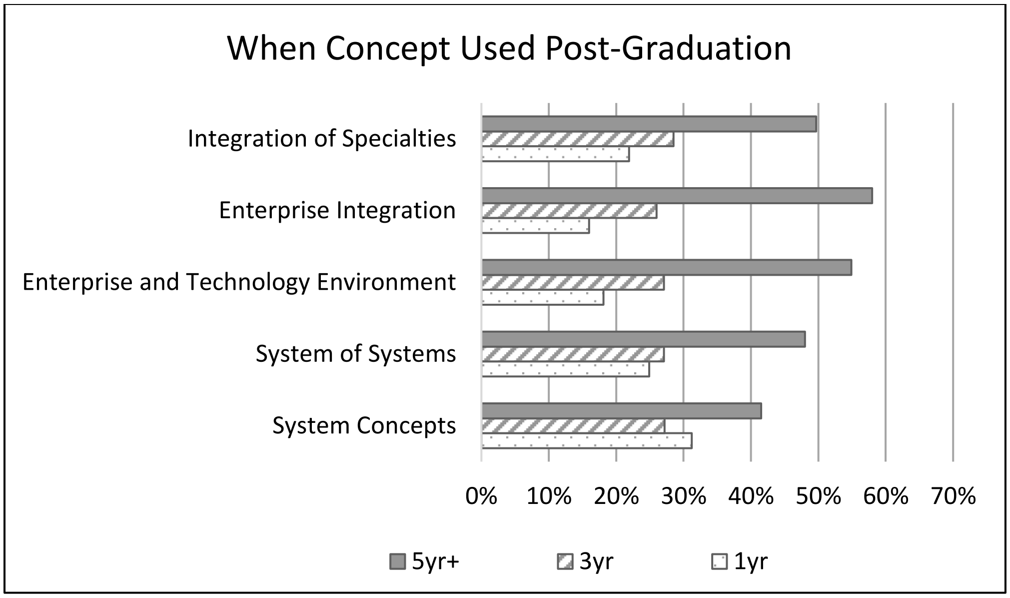


Figure 8: Systems Thinking When Concept Used

Participants are also given the opportunity to enter free response text commenting on those competencies listed. These responses are separated into three areas: industries in which the participant was exposed to the competency (shown in Table 15), those relating to learning the competency (shown in Table 16), and general comments. A summary of responses is presented below. A full listing of responses can be found in the appendix.

Table 15: Systems Thinking Industries

Industries Mentioned	
Information Technology [4 comments]	Piping and Instrumentation Diagrams Development Lead
Electrical Engineering and Controls [2 comments]	Medical Field
Software Systems	Chemical Processing (Dow Chemical)
Automotive (Honda new product development)	Role in start-up of new processes and systems
Aerospace (Navy Officer, Spacecraft, Satellites)	

Table 16: Systems Thinking Learning

How to Learn
On the job.
After fundamentals are learned and well understood.
After years of experience.
"Senior design projects bridging engineering disciplines….years of experience required …. to build a vision for how to best integrate large multidiscipline design features”
“Job environment most effective teacher of detailed systems but basic integration education should be understood before graduation. “
Difficult to teach…. appreciation comes after experience.

Selected responses that reveal participant perspectives on competencies:

- Vernacular is unfamiliar [10 comments] …. but seems to relate to my experiences.
- Systems engineering means different things at different companies and organizations.
- “My ability to execute came after 20 years of experience in multiple parts of the oil and gas industry”
- “The fact that this is being surveyed is awesome”
- “This is a great skill for engineers to develop. It is mandatory if one wishes to move into management”
- “Interactions with other departments should be taught in UG MEEN curriculum”
- “For the major international, billion-dollar projects engineered…. systems engineering was an integral part of every successful project. It was likely the most challenging part of training for any new graduate.”
- “Systems Concepts throughout education. Enterprise and Technology Environment: 1st and 4th year, System of Systems: specialized course as part of System Concepts. Remaining, include in Systems Concepts and 3rd and 4th year. “
- “Too many engineers are too functionally specific and need to back off and view it from a systems perspective. The best engineers have this ability and often allows them to advance faster.”

- “Enterprise Integration would be better learned on the job. The rest are skills that would benefit graduating engineers as a good population will enter relevant roles someday.”
- “At the UG level, beneficial to understand System Concepts and overview of System of Systems, maybe an overview of the next three [Enterprise and Technology Environment, Enterprise Integration, Integration of Specialties], but too much to delve much deeper into Systems Engineering at the UG level.”
- “Design engineering, marketing, sales, management, and business have involved understanding that very few things operate alone….people, machines, and machine components.”
- “Based on young engineers I have seen in my career of working with them [and] hiring them, they have no concepts of systems. It should be taught.”
- “Enterprise and Technology Environment is very important.”

4.1.4 Section 2 Results- System Lifecycle Design

The second section is composed of high level systems engineering competencies grouped under the title System Lifecycle. Participants were asked to indicate their level of competency for each, selecting from “none”, “familiar with” or “able to execute”. A summary of these results can be seen in Figure 9.

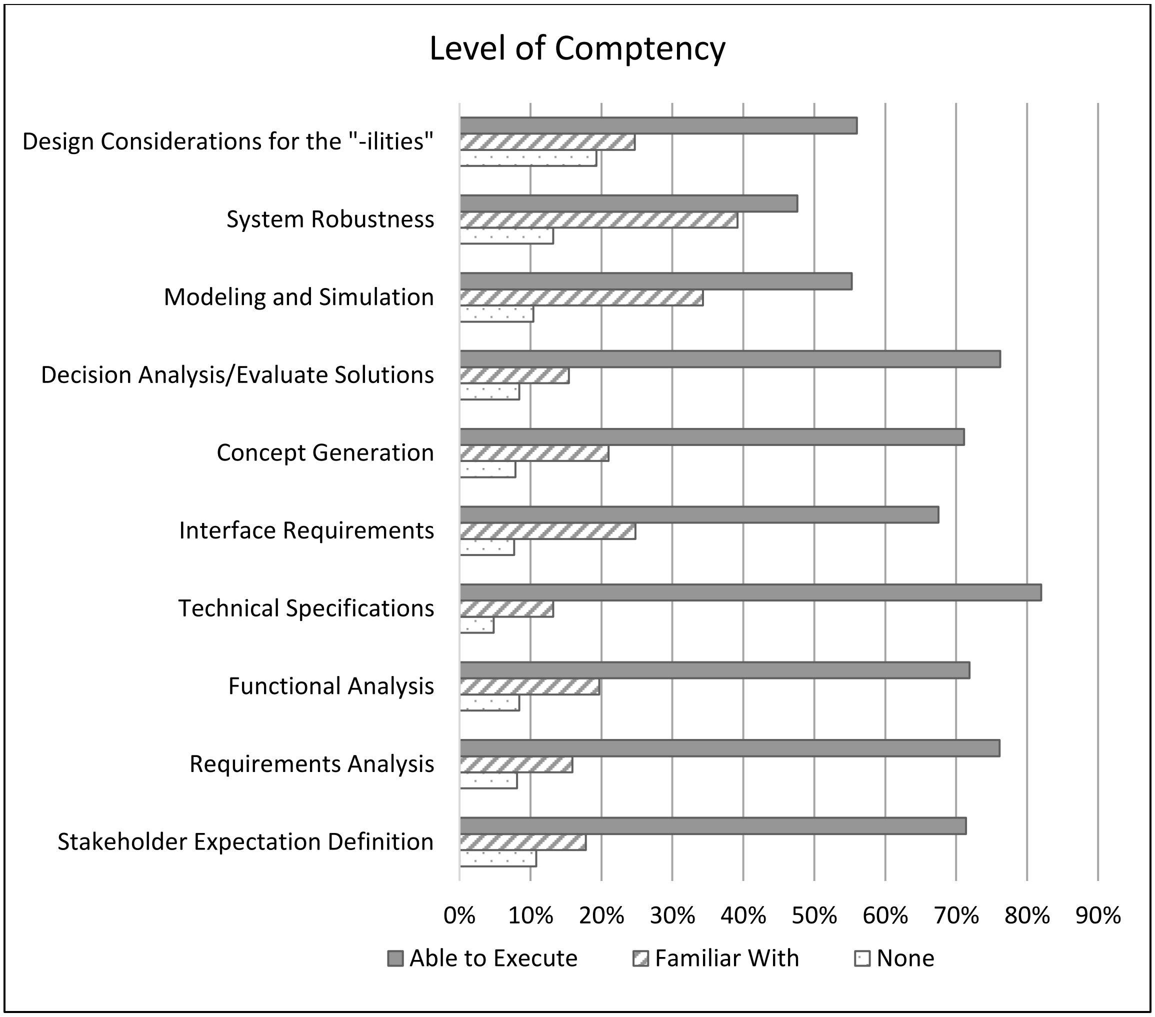


Figure 9: Level of Competency

Respondents are then asked to select how they learned this concept. They may select more than one from the following choices: undergraduate mechanical engineering education, on the job or through graduate education. Graduate education includes a certificate program as well as a masters or doctoral degree. Results are shown in Figure 10.

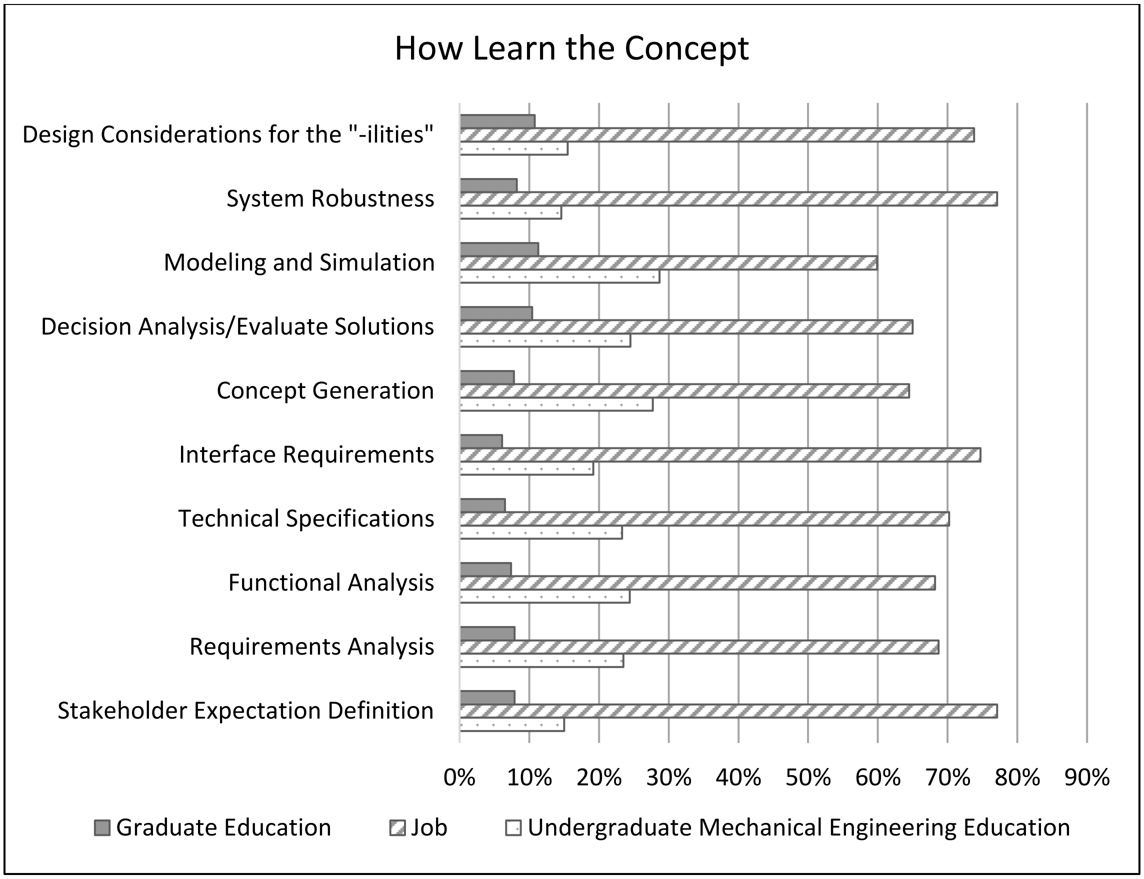


Figure 10: System Design Learning

Next, participants are asked if they would recommend this concept to be included in a mechanical engineering undergraduate curriculum. Choices are “yes” or “no”. Results are in Figure 11.

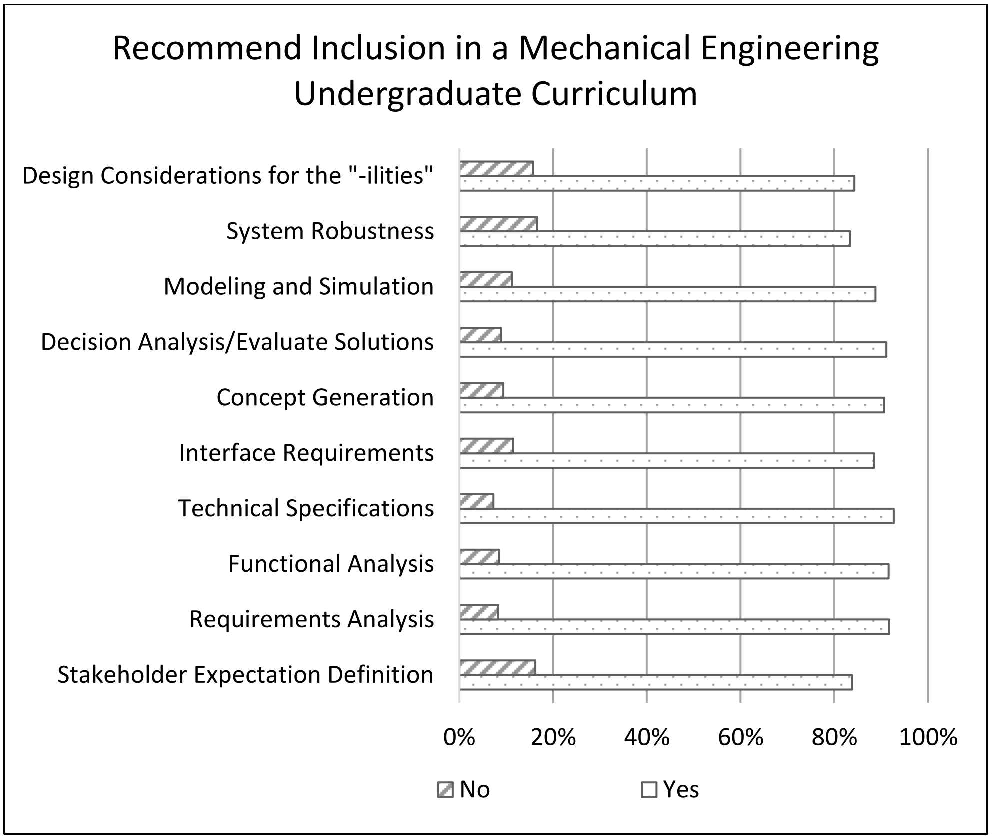


Figure 11: System Design Curricular Inclusion Recommendation

Finally, participants are asked at what point after their graduation with their BS in Mechanical Engineering they used each concept. Results are shown in Figure 12.

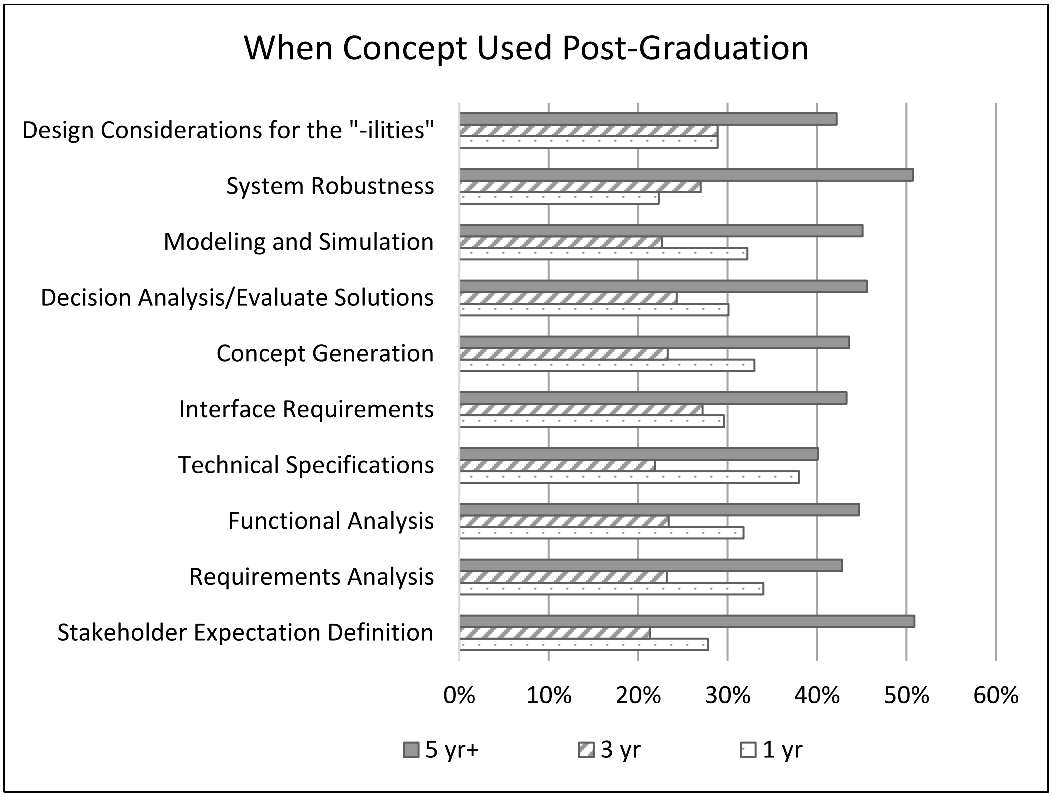


Figure 12: System Design When Used

Participants are also given the opportunity to enter free response text commenting on those competencies listed. These responses are separated into three areas: industries or applications in which the participant used the competency (shown in Table 17), those relating to learning the competency (shown in Table 18), and general comments. A summary of responses is presented below. A full listing of responses can be found in the appendix.

Table 17: System Design Industries

Industries and Applications of Competencies
Oil & Gas (Chevron)
Complex Aerospace Systems & NASA Project Management
Defining success criteria for new product development under the head of Product Life Cycle with stage gates of our latest embodiment of system development we call Product Development Engine…..We look at design for cost and design for reliability….certainly valuable as you think of how to develop a successful product.
Most of these were not covered in my education in the 1970s…most of my applicable skills/concepts came from MBA classes in the mid-1990s

Table 18: System Design Learning

Comments Highlighting Specific Competencies and How to Learn Them
Some should be taught at the graduate level, thus “no”.
Beneficial, step in the right direction, awareness [7 comments]
One class can explain all of these. I’ve used these without being aware. Don’t need to be an expert unless going into a systems engineer role
Hard to go deep in all of these areas in a high level design class. However, good exposure to these topics goes a long way to building engineering leadership
I actually have thought this is what was missing in my formal education….how to put it all together. It takes years for younger engineers to develop these skills.
[These are] practical concepts would expect a new engineer to be familiar with. Most of these are fundamental to being an effective engineer who can problem solve in an effective manner.
Case studies
Exposure to case studies within some of the traditional ME curriculum could make the **sophomore/junior level class more relevant**. Answered “no” to the questions because they are too industry specific and would not be possible to cover effectively.
Concept level with industry case studies….highly industry specific: Design for Considerations for the “-ilities”, System Robustness, Technical Specifications, Interface Requirements. Remaining concepts should be taught with more rigor…engineers going into industry should be well equipped to execute.
Practical application important [3 comments]
Problem solving skills important [2 comments]
Project Management/Project Engineering/Leadership roles use these [6 comments]

Table 18 (con't)

Comments Highlighting Specific Competencies and How to Learn Them
Coursework should address, at the very least, (1) the concept of system life expectancy (2) additional costs for operating a system are incurred for more critical or complicated systems
Design for Considerations of the "-ilities". I wish I had more exposure to this in UGME. It's a key part of my job and I had to learn it early on.
Manufacturing is a key skillset….ME's need more education on.
Design for Manufacturability and assembly, manufacturing methods and evaluation, design analysis...test what you build. **Should** happen **before senior design** and **must** happen **in senior design.**
Courses in Decision Analysis
Stakeholder Expectation Definition
Requires on job experiences specific to each stakeholder involved.
Stakeholder Analysis is key
Courses in Stakeholder Identification
With 31 of my 33 years of experience as a project manager on small to medium size maintenance and capital projects, I have executed many projects requiring definition of stakeholder requirements….
Interface Requirements [2 comments. See below.]

Selected responses that reveal participant perspectives on competencies:

- "In my education in 1985 it was aimed at making everyone a design engineer but did very poor at training engineers to design things that could **actually be built**." Poor in the area of **interface requirements.**
- **Stakeholder Management, Concept Alternative Identification and Evaluation, Decision Making/Analysis** is core at Chevron. Being able to execute these competencies coming out of school will enable engineers to differentiate themselves early in their careers.
- One of my biggest shortcomings ....was the lack of education towards **machine design** and **reliability engineering**. These should be courses instead of on the job learning.
- "Today's products may require more exposure in the engineer's education to concepts such as **interface requirements**"

4.1.5 Section 3 Results- System Lifecycle Implementation

The third section is composed of high level systems engineering competencies grouped under the title System Lifecycle Implementation. Participants were asked to indicate their level of competency for each, selecting from "none", "familiar with" or "able to execute". A summary of these results can be seen in Figure 13.

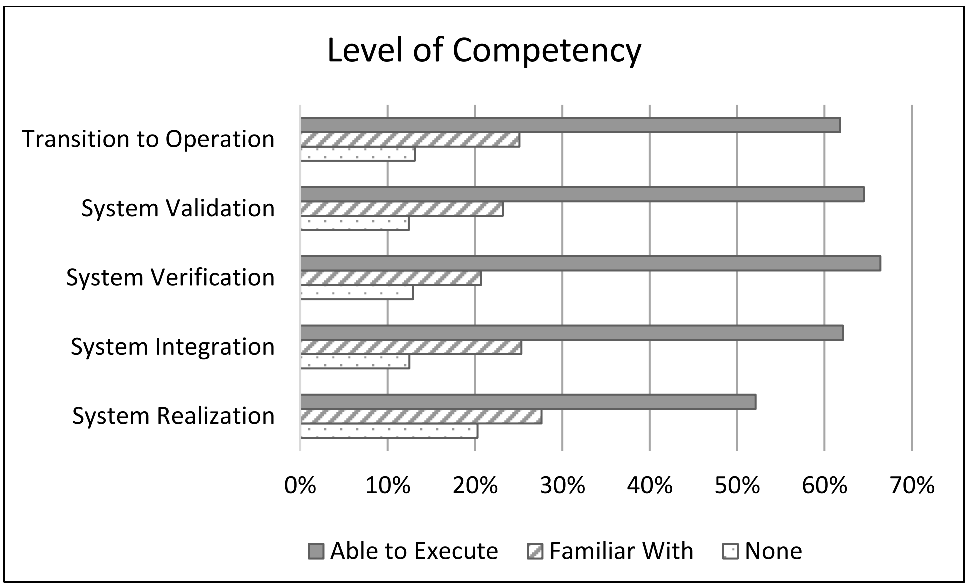


Figure 13: System Implementation Competency Level

Respondents are then asked to select how they learned this concept. They may select more than one from the following choices: undergraduate mechanical engineering education, on the job or through graduate education. Graduate education includes a certificate program as well as a masters or doctoral degree. Results are shown in Figure 14.

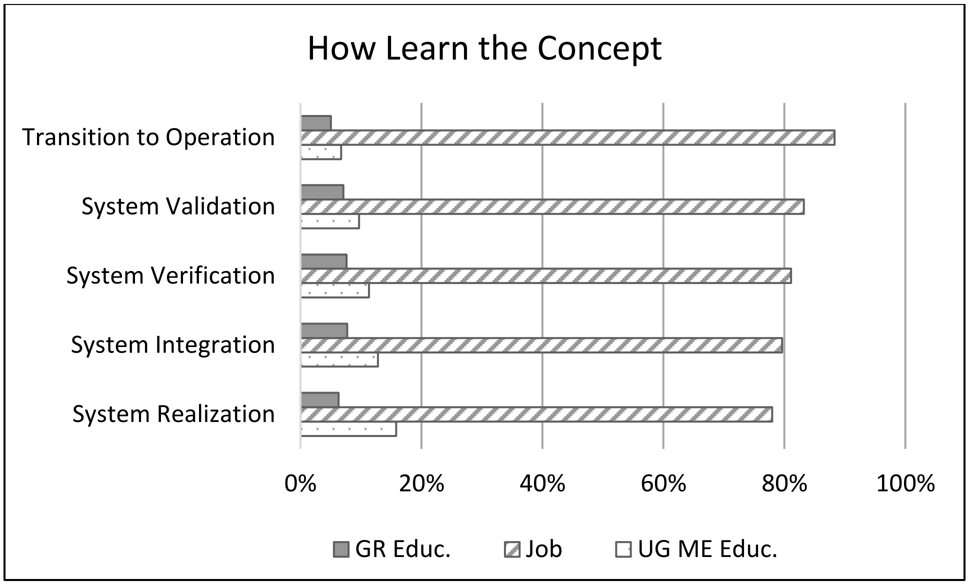


Figure 14: System Implementation Learning

Next, participants are asked if they would recommend this concept to be included in a mechanical engineering undergraduate curriculum. Choices are "yes" or "no". Results are in Figure 15.

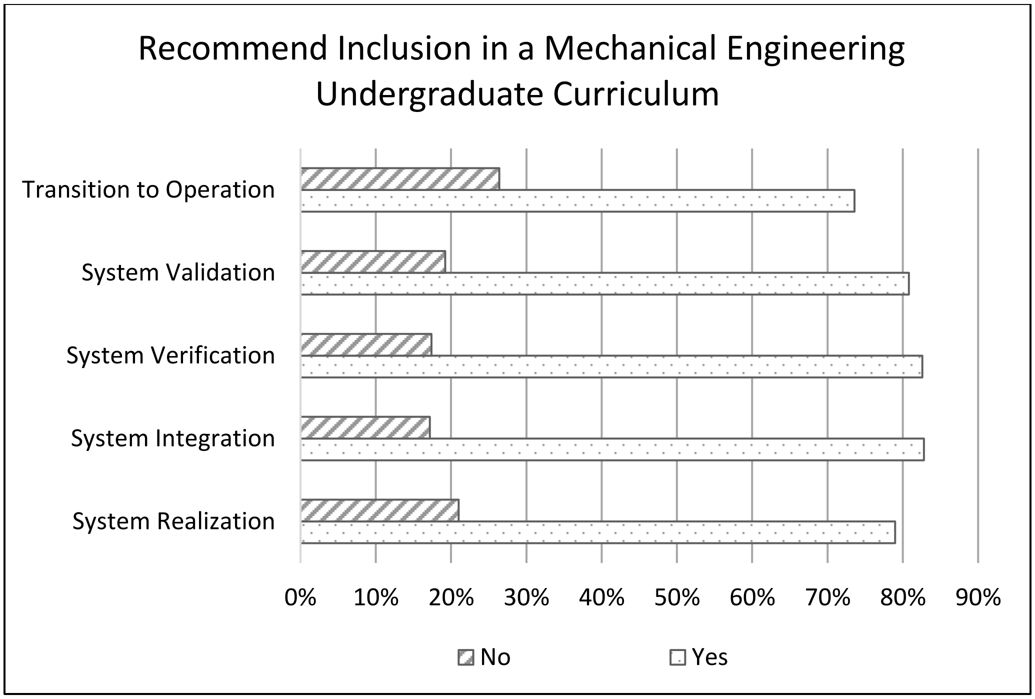


Figure 15: System Implementation Curricular Inclusion Recommendation

Finally, participants are asked at what point after their graduation with their BS in Mechanical Engineering they used each concept. Results are shown in Figure 16.

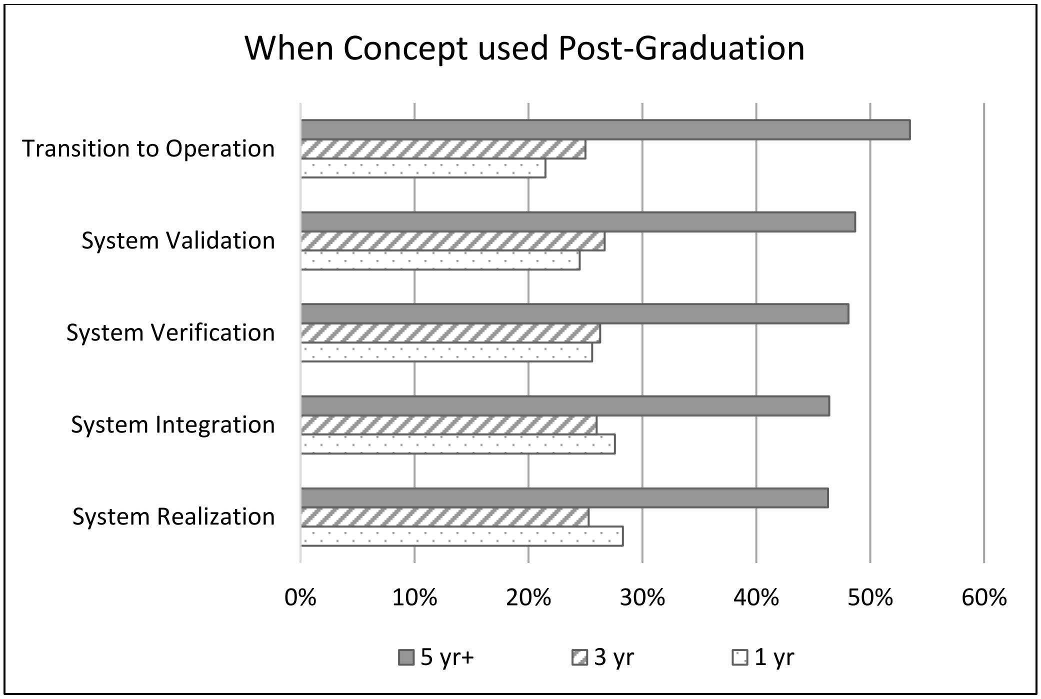


Figure 16: System Implementation When Used

Participants are also given the opportunity to enter free response text commenting on those competencies listed. These responses are separated into three areas: industries in which the participant used the competency, learning the competency, and general comments. A summary of responses is presented below. A full listing of responses can be found in the appendix.

Table 19 presents responses regarding industries or job functions in which these competencies are used.

Table 19: System Implementation Industries

Industries Mentioned
Manufacturing: developed early in an engineer's career working in manufacturing environment and developed over time. For an operator, such as Chevron, competencies are only developed if engineer's assignment requires them.
Oil & Gas (deep water major capital projects, other/general industry)
Automotive: not much time on design but instead interfacing with manufacturing and validation organizations.

Several comments are made regarding students learning these concepts and curricular inclusion. One respondent is concerned about what would be removed to add this information. Still another said this is too "in the weeds" for an undergraduate degree. This aligns slightly with six respondents who commented that these competencies are very industry-specific. Three of these comments also said the terms are different than what they use, but the ideas are valid and important and implemented in their jobs. Comments mentioning specific competencies are summarized in Table 20.

Table 20: System Implementation Learning

Comments Highlighting Specific Competencies to Learn
Transition to Operation
Least important.
Often a weak point.
The engineer should guide the testing, validation and implementation acceptance. Technical aspects of what factors into a successful deployment are engineering functions.
When teaching test and evaluation, ensure the independence of T&E from SE is stressed and that the item failing a test generally means the item failed, not the test.
System testing and transition to normal operations was a gap in my undergrad and very important in most industries.
Basic systems engineering/value engineering would be a useful addition to the engineering training program.
Bring in owners of programs and set up mentorship programs.

Selected responses that reveal participant perspectives on competencies:

- Learning “root cause” system analysis methodology would help…as that typically led to system improvements and illustrates need for systems.
- These are essential in program management.
- Learning about the necessities of these steps in a system lifecycle was ey-opening when I started working.
- Appreciation of systems approach is very important and becoming more prominent in aerospace industry. Highly recommend some level of systems engineering coursework for all ME students.
- Engineers need to understand what needs to happen to get their designs off the drawing boards and into the real world customer’s hands.

4.1.6 Results Section 4- Management

The fourth section is composed of high level systems engineering competencies grouped under the title System Management. Participants are asked to indicate their level of competency for each, selecting from "none", "familiar with" or "able to execute". A summary of these results can be seen in Figure 17Figure 17: System Management Competency Level.

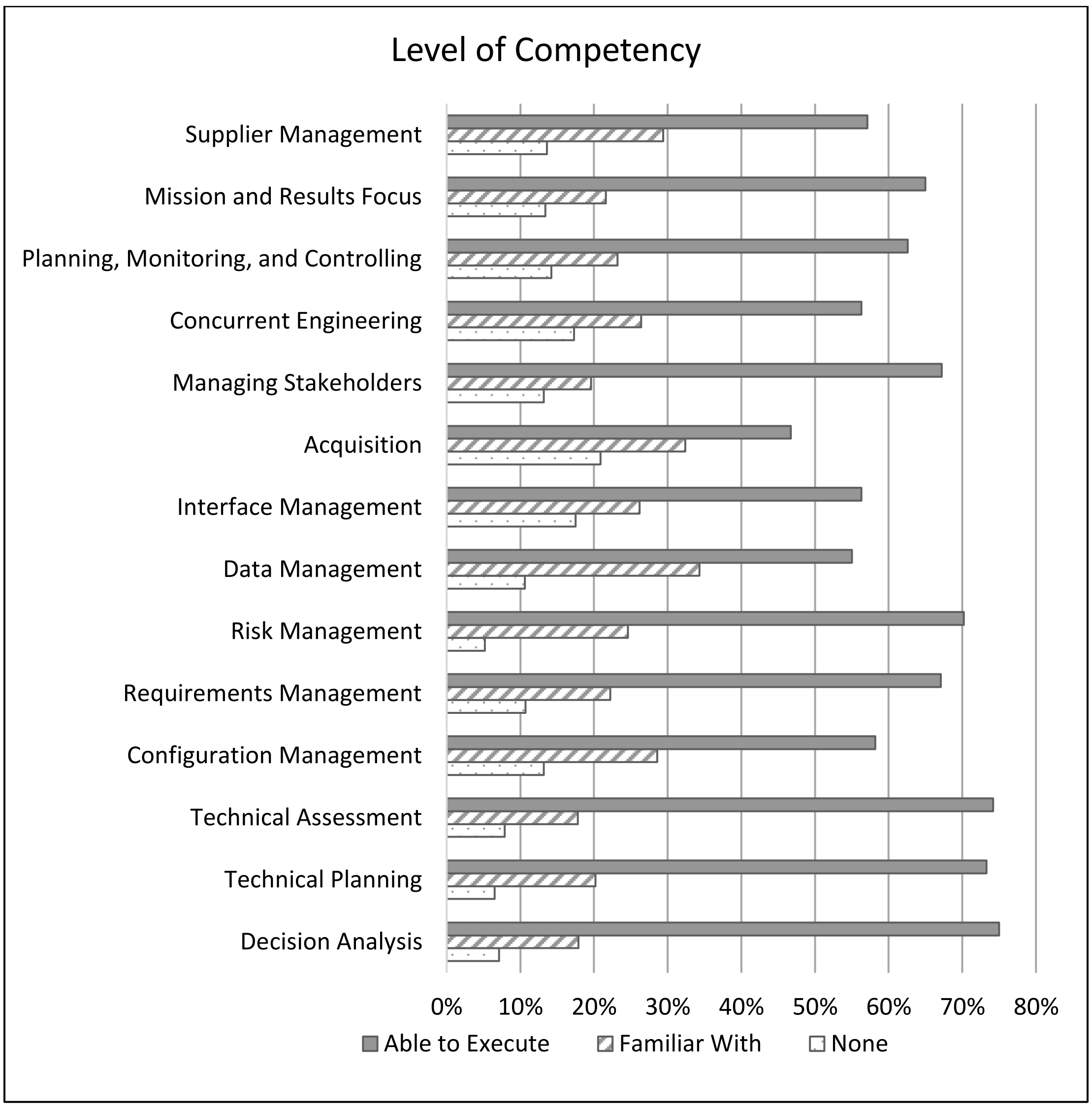


Figure 17: System Management Competency Level

Respondents are then asked to select how they learned this concept. They may select more than one from the following choices: undergraduate mechanical engineering education, on the job or through graduate education. Graduate education includes a certificate program as well as a masters or doctoral degree. Results are shown in Figure 18.

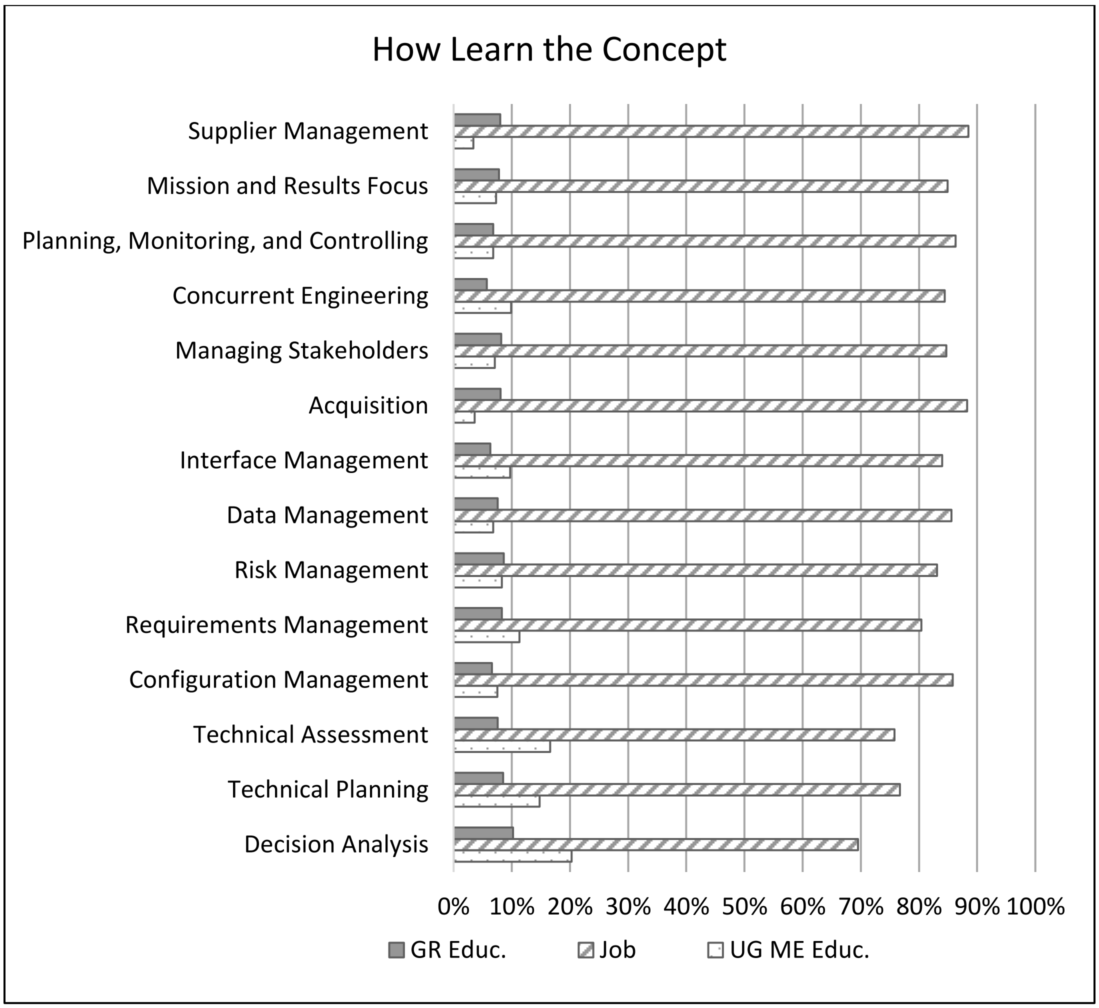


Figure 18: System Management How Learn

Next, participants are asked if they would recommend this concept to be included in a mechanical engineering undergraduate curriculum. Choices are “yes” or “no”. Results are in Figure 19.

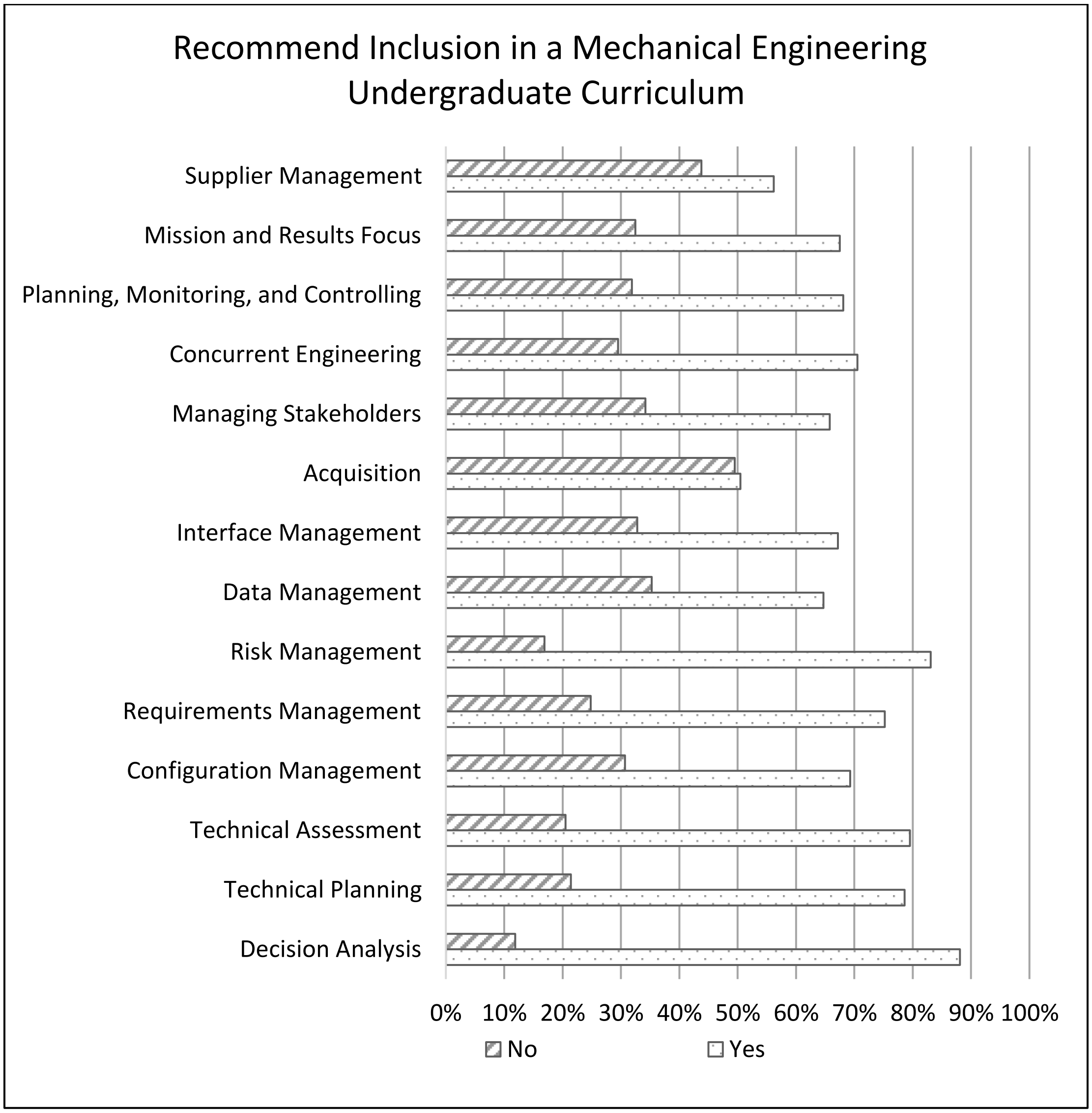


Figure 19: System Management Curricular Inclusion Recommendation

Finally, participants are asked at what point after their graduation with their BS in Mechanical Engineering they used each concept. Results are shown in Figure 20.

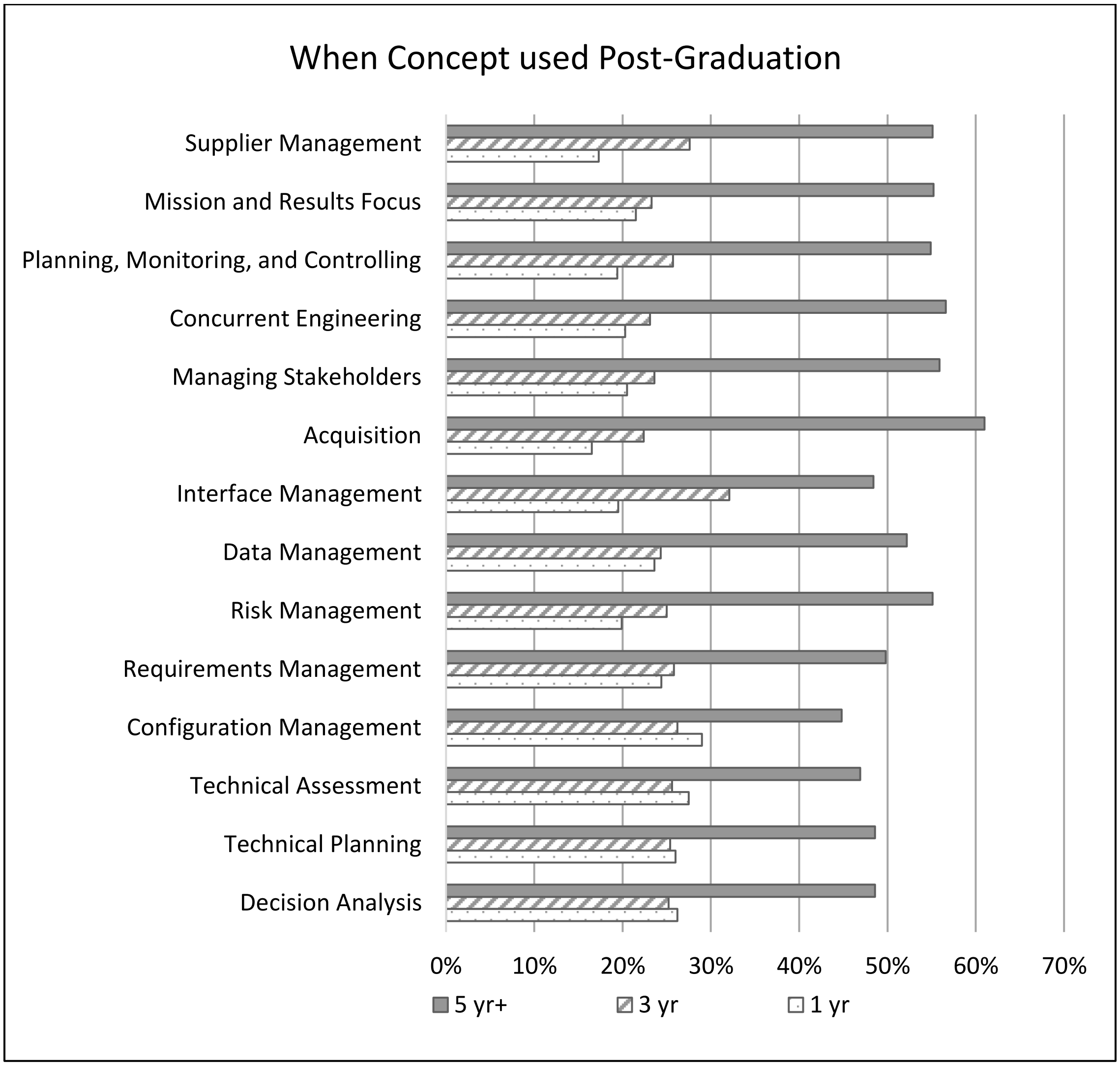


Figure 20: System Management When Used

Participants are also given the opportunity to enter free response text commenting on those competencies listed. These responses are separated into two areas: industries in which the participant used the competency (shown in Table 21) and learning the competency (shown in Table 22). A summary of responses is presented below. A full listing of responses can be found in the appendix.

Table 21: System Management Industries

Industries Used
System design, manufacture and test programs
"For the medical device field, risk management is a very important and time consuming part of my job."

Table 22: System Management Learning

How to Learn
Learn on the job
These particular competencies are very unique to different industries and companies [8 comments]
Need experience and context to fully learn the topic. [4 comments]
Value in undergraduate students having a **general awareness** and **conceptual idea** of these competencies. [6 comments]
Mastery of these competencies would be most **advantageous** to graduates [2 comments]
These would fall under a "Technical Project Management umbrella" knowledge of which is critical to an engineer's success.
Too specific and "in the weeds" for a mechanical engineering undergraduate education [2 comments]
Teach in graduate school
"Management for the most part understands the concepts, but struggle with the role of implementation."
A comment that these are technical management and leadership related competencies and could be an engineering management set of electives.
Managing stakeholders: concept and importance
Supplier Management (Logistics): need to understand the importance

4.1.7 General Comments regarding Systems Engineering Education for Mechanical Engineers

The survey concludes with an open-ended question asking for any feedback, thoughts or comments on including systems engineering concepts in a mechanical engineering undergraduate curriculum. Additional comments left by participants included a wide range of opinions regarding how much systems engineering concepts should be taught and to what level. An overwhelming majority validated the reality of working in a systems-centric environment in which it is helpful, and necessary for some, to have a system-level awareness and ability to function in a multi-level project environment. Many respondents also pointed out that as they progressed in their career, they moved into project management or similar role in which they operate at the system level and must understand the interplays of each subsystem.

One hundred and fifty free response comments are in this section. Each response is read and the main idea(s) pulled from the response. It is possible to have more than one main idea in the response. These ideas are tallied and then further grouped into themes. A full listing of responses can be found in the appendix.

The main themes in the responses included the level of need of systems engineering in an mechanical engineering undergraduate education, the amount of detail required in the curriculum, some ideas on how to include in the curriculum, suggestions on specific topics to include in the curriculum, and some feedback on how the respondent has used systems engineering concepts in their job and/or career. Those topics not relevant to systems engineering are not presented here.

The level of need of systems engineering and systems concepts is described in the responses using various terminology which are shown in Table 23. Key words are tallied and grouped in two different levels: critical and important/relevant.

Table 23: Level of Need for Systems Engineering Inclusion in Mechanical Engineering Curricula

Level of Need		
Important/Relevant (65)	Beneficial	10
	Dominant competency to have	1
	Helpful	14
	Important	16
	Recommend	3
	Relevant/Pertinent	4
	Should be included	10
	Valuable	7
Critical (27)	Critical	7
	Essential	6
	Integral	3
	Key to success	1
	Need	7
	Vital	3

Forty-three responses include statements on how much exposure to systems engineering the students should receive. Various terminology was used, but overall respondents suggest a basic introduction to systems concepts. The verbiage used is listed in Table 24 below.

Table 24: Level of Systems Engineering Content for Inclusion in Mechanical Engineering Curricula

Level of Instructional Detail	
General knowledge/ awareness/concepts	15
Exposure	6
Familiar	5
Basics	4
Introductory	4
Overview	4
Background	2
Competency	1
Light Touch	1
Survey Level	1

One apparent concern of respondents is removing part of the existing curriculum to replace with systems engineering concepts. Thirteen comments state that the curriculum must focus on the basics of engineering and the fundamentals. Two participants mention the importance of remaining practical and not going too heavy on the “theory” or “academic” perspective. Thirty-two comments suggest ways to include systems engineering in the curriculum. The most common suggestion is an introductory course. A few suggest using “real world” or “real life” projects as examples and teaching aides. One person suggests creating a 4+1 program in which the student earns both a bachelor of science in mechanical engineering and a master of science in systems engineering. Another recommendation is to invite speakers from industry to give a one hour overview on the use and application of systems engineering in their industry. Still another suggests to capitalize on opportunities to be involved with co-curricular activities as a way to gain a “broader worldview”, develop practical skills and be prepared to meet industry’s need for “enterprise-level thinking”. A summary is shown in Table 25.

Table 25: Methods to Introduce Systems Engineering in the Curriculum

Educational Methods	
Standalone course (elective, intro course, specific topic)	16
"Real life" engineering project in cooperation with a company/ real world examples	6
Previous exposure in senior design during undergraduate curriculum	6
4+1 program (BS ME, MS SE)	1
Include software development perspectives of systems engineering	1
One hour speaker sessions	1
Utilize co-curricular activities for enterprise-level thinking skills	1

Eight respondents recognize that mechanical engineers often take a leadership role and their broad education primes them well to assume these and systems engineering type positions. The position titles mentioned are: Project Engineer, Lead Engineer, Technical Manager, Project Manager, Functional Manager, and Engineering Manager. One mentioned s/he often feels like a systems engineer.

Respondents also state specific topics they have used or indicate is important to know. A summary and count of these as related to the systems engineering competencies identified in the survey questions are found in Table 26.

Table 26: Systems Engineering Competencies Mentioned by Participants

SE area: requirements definition	9
SE area: integration	8
SE area: management	6
SE area: "-ilities"	4
SE area: product life cycle	4
SE area: systems concepts	4
SE area: design	3
SE area: integration of specialties	3
SE area: transition to operation	3
SE area: decision analysis	2
SE area: stakeholder expectation	2
SE area: system realization	2
SE area: concept of operations	1
SE area: economics	1
SE area: interfaces	1
SE area: model based engineering	1
SE area: risk management	1
SE area: stakeholder management	1
SE area: validation	1
SE area: verification	1

Several respondents oppose teaching these in the undergraduate education. The following reasons are identified: these concepts are best learned through practical experience, they would be difficult to teach in a course without the context of real world problems and experience, and they are too specific to teach in a class and would be best learned at the specific company to learn their processes. In particular, the diversity of how companies and industries define, interpret and implement systems engineering definitions and processes is mentioned in the comments. Several respondents also indicate they learned these on the job. Some also comment on the importance of students to have a solid foundation in the basics and fundamentals of engineering, math and science. A tally of these additional considerations are summarized in Table 27.

Table 27: Other Considerations

Vary by company/industry	11
Practical experience	11
Learned on the job	10
Engineering fundamentals	10

Comments related to how systems engineering is used in a specific industry or job are presented in Table 28.

Selected responses that reveal participant perspectives on competencies:

— Modern engineers are expected to be salesmen, purchasers, planners, manage logistics, work with stakeholders; they're the whole package.

— Reliability/systems engineering was not implemented in my company/industry until later in my career (1990s). Definitely need curriculum to allow a graduate to attain "certification" without a concerted effort outside of their formal education.

— Too much of the mechanical engineering curriculum degree I received focus on detailed analysis. My industry uses specialized resources to complete these analysis. Most engineers just need to be able to speak their language and interpret results. More**, higher level thinking** and expansion beyond these concepts should be included.

— UG classes should prepare graduates to work on a **systems management team**. They should be able to step into various roles on the team.

Table 28: Systems Engineering Industries Used

Industries Used
Manufacturing: Building complex semiconductor equipment, we **rely on it completely** to align the efforts of large cross functional teams to a staged, well defined, long term set of goals. I did not get involved in these topics for more than **ten years after graduation**.
Navy: Concepts from a systems standpoint are useful to a Navy pilot who helps "build requirements for current and future platform capabilities."
Heating, Ventilation, Air Conditioning (**HVAC**): I must understand how all systems function together and relate to other systems within a project. If the UG degree can **provide more systems concept tools** that it has taken me years to develop, the young engineers will be **extremely valuable to the industry**.
Aerospace (**Hughes Aircraft satellite division**): Systems Engineering is the pathway to upper management. I was a systems engineer for 6 of my 7 years as an engineer before I stepped into a technical management role. **Very key to my success.**
Product development engineer: For my entire 7 year career, these concepts are very relevant. I would say that upwards of **60% of my time is devoted to concepts such as these**. A learned and trained ability to manage multiple projects that are all part of a complex system of projects would be very beneficial coming out of college.
P**roject Management**/Project Engineering
Essential for managerial or project positions. Needed for technical or research positions to understand how work fits into overall project.
Very important. We hire MEs that **begin in project engineering**.
As career progressed with higher levels of engineering management, begin to take a holistic view of equipment and systems, resulting in a systems view.
As a lead **Systems Engineer** or **Chief Engineer** you must have a very diverse skill set and learning all these would be very valuable.
Design: Important for **product and component level designs**; a must for full **life cycle design**.

5. ANALYSIS AND DISCUSSION

This chapter presents an analysis of the survey results and application of this analysis to suggestions on how to incorporate systems engineering concepts into a mechanical engineering undergraduate curriculum. Faculty feedback on curricular inclusion is also presented.

5.1 Survey Results

Several takeaways can be gleaned from this survey. Overall, when asked if systems engineering competencies should be included in a mechanical engineering undergraduate curriculum, the responses are affirmative. Only the two competencies “Acquisition” and “Supplier Management” are not necessary for inclusion in an undergraduate curriculum according to the responses. Enterprise Integration is not recommended for inclusion by those with a System Engineer title and not recommended by 50% with a Mechanical Engineer title. Enterprise Technology Environment is not recommended by 50% with a System Engineer title. All other competencies have a higher percentage of recommendation for inclusion, some 100%, by those with a System or Mechanical Engineer title.

The level of competency most respondents indicate is “able to execute”. In the first section “Systems Thinking”, responses are distributed among “none”, “familiar with” and “able to execute” with a majority level above “none”. The competency “System Concepts” has the highest level with 33% “familiar with” and 55% “able to execute”. The remaining sections of competencies show a majority level as “able to execute”. When filtered by title, System Engineers respond over 50% “able to execute” in the “Systems Thinking” area and over 90% in the other sections, except the competency “Transition to Operation” which is 75%. Those with Mechanical Engineer titles have slight variations, but follow a similar profile. For management titles, there are a higher percentage of “able to execute” responses and less “none”. Mechanical engineering graduates use these competencies at varying levels depending on their job title.

The majority of respondents learned systems engineering concepts on the job. All responses for learning systems engineering competencies in undergraduate school is less than 30%. Those competencies learned in school by 20%-30% of respondents are listed in Table 29.

Table 29: Participant Learned Competencies

Competency Learned in Undergraduate Education	
Systems Engineering Competency	**Responses**
System Concepts	25.7%
Requirements Analysis	23.5%
Functional Analysis	24.4%
Technical Specifications	23.3%
Concept Generation	27.7%
Decision Analysis/Evaluate Solutions	24.5%
Modeling and Simulation	28.7%

While these percentage are low in comparison to responses for “learned on the job”, they are higher percentages than other competencies which are mostly under 10%. This reveals a slight indication that these competencies are included in some undergraduate education curricula. Most of these competencies are grouped with “System Design”, which would correlate with a senior capstone design course. A few free response comments mentioned learning concepts in this course. Given the low percentage and considering most respondents are graduates of the same institution over a sixty-year period, this reveals possible variation in detailed course content over time and influence of instructor on course materials. Filtering results by those with 3-8 years of experience, a slightly higher percentage indicate learning in undergraduate and graduate school. This may indicate a more recent trend in systems engineering concepts being introduced into the curriculum. Filtering results by title, those with System Engineer indicate a higher percentage of learned concepts in graduate school while those with Mechanical Engineer or Engineer indicate a higher percentage of learning in undergraduate education. Those with a management or leadership title indicate a higher percentage of learned on the job. While there may be sporadic inclusion of these competencies, it is clear that the remaining competencies are not adequately covered.

In terms of when graduates use all competencies in their jobs or careers, most use them five or more years after graduating with their mechanical engineering bachelor's degree. Approximately 20-30% of respondents use them less than five years after graduation. Filtering results by title, Systems Engineers use most competencies one year after graduation. Mechanical Engineers vary depending on the competency but overall use them earlier than five years after graduation. Those with Engineer in their title respond with a higher percentage used at one year after graduation, but overall the majority use after five years. Those with management or leadership titles respond with a higher percentage of management competencies after five years.

Respondents performing in a system engineer role with a current title of Mechanical Engineer received formal training through their employer's training program (55%), a degree (22%) or other (22%). Respondents with a management title who received formal training in systems engineering indicate 53% from a degree, 6% from a certificate or minor, 31% through employer training and

9% other. Those with a System Engineer title received formal training through a degree (50%), certificate or minor (16%), or employer training (33%). Overall, it appears that mechanical engineering graduates who perform in a systems engineer role receive formal training either through a university degree (which may include their undergraduate degree) or through a training program by their employer.

Free response comments indicate a need to at least provide an awareness to students of these competencies. Some commented on the necessity for work experience to provide a context in which to apply these concepts. Still others promoted such concepts as vital for career progression. It can be seen that at the minimum, exposure to these concepts is needed for undergraduate mechanical engineering students.

Overall respondents state that systems engineering and a systems level view and appreciation is important and should be taught at the undergraduate level. Respondents mainly use these skills five or more years after graduating with their bachelor degree in mechanical engineering.
The next section summarizes an analysis of current undergraduate mechanical engineering programs and their inclusion of systems engineering concepts. Subsequent sections discuss approaches to inclusion of these concepts in mechanical engineering curricula.

5.2 Mechanical Engineering Curricula Review

Top ranking U.S. engineering and mechanical engineering programs are reviewed in search of systems engineering inclusion at the program level and woven into the curriculum. The following fourteen programs listed in Table 30 are selected based upon their program ranking according to the 2018 U.S. News and World Reports [64]. Those with an asterisk are top ranked engineering programs, all others are top ranked mechanical engineering programs. Another selection criteria is programs that are part of a large, public institution with high enrollment and large faculty size for mechanical engineering. This profile matches that of the survey respondents' alma mater and indicates a high number of graduates entering the workforce from the institution. Each program is reviewed for mention of systems engineering or systems thinking in their program objectives, program outcomes or course titles.

Table 30: U.S. Top Ranked Mechanical Engineering Undergraduate Degree Programs

Mechanical Engineering Program Ranking by US News and World Report for 2018	
Ranking	Institution
1	Massachusetts Institute of Technology
2	Stanford University
3	Georgia Institute of Technology
4	University of Michigan-- Ann Arbor
5	University of California -- Berkeley
6	Purdue University—West Lafayette
6	University of Illinois at Urbana-Champaign
8	California Institute of Technology
10	University of Texas—Austin
12	Texas A&M University—College Station
14*	University of Wisconsin
14*	Virginia Tech
20*	Pennsylvania State University

*14 best engineering programs
*20 best engineering; large public university

Upon review, only two mechanical engineering undergraduate programs included systems-related verbiage in their program overview outside of ABET criteria verbiage related to systems. This

ABET verbiage includes Student Criterion C: "An ability to **design a system**, component, or process to **meet** desired **needs** within realistic constraints such as economic, environmental, social, political, ethical, health and **safety**, **manufacturability**, and **sustainability**". Those words in bold relate to principles of systems engineering. The two institutions with additional program-level verbiage are at Massachusetts Institute of Technology (MIT) and California Institute of Technology (CIT). The systems-related verbiage is shown in Table 31. MIT's educational objective includes implementation in addition to design, and CIT's objectives mention the formulation and optimization of systems in addition to design, incorporating important elements of systems engineering.

Table 31: Undergraduate Mechanical Engineering Program Objectives with Systems-Related Verbiage

Institution	**Program Verbiage Referencing Systems/Systems Engineering**	**Systems Engineering Degree Offered**
MIT	Educational Objective: Lead in the conception, design, **and implementation** of new products, processes, services, and **systems.**	Professional Courses *(Continuing Education)*
California Institute of Technology	Importantly, the field also emphasizes the process of **formulation**, design, **optimization,** manufacture, and **control of new systems** and devices. http://www.mce.caltech.edu/academics/ugrad	n/a

In search for motivation as to why these two institutions include such verbiage, an additional search for systems engineering degrees offered is completed revealing that neither school offers such a degree. MIT does, however, offer professional courses in systems engineering and CIT offers an undergraduate multidisciplinary system engineering course. To note is that only three of the fourteen institutions reviewed offer a degree in systems engineering and all are at the graduate level. Texas A&M University College Station campus offers a Master of Engineering in Systems Engineering. Pennsylvania State University Great Valley campus offers a Master of Engineering in Systems Engineering; however, this campus location does not offer an undergraduate mechanical engineering degree. The University of Wisconsin Madison offers three domain-centric systems engineering degrees: Master of Engineering: Sustainable Systems Engineering (online), Masters of Science in Industrial Engineering – Human Factors and Health Engineering, and Masters of Science in Industrial Engineering – Systems Engineering and Analytics.

After reviewing the courses in the curriculum, there is only one institution, Georgia Institute of Technology, that offers a standalone system engineering course, and it is not required. The impression is that systems engineering concepts are incorporated into the degree program (domain-specific approach). Five other institutions incorporate systems-verbiage in a course description. These course descriptions are shown in Table 32 with systems-related text in bold.

Table 32: Undergraduate Mechanical Engineering Programs with Systems-Related Courses

Institution	Systems-Related Courses
Stanford	*ME 170A: Mechanical Engineering Design- Integrating Context with Engineering* First course of two-quarter capstone sequence. Working in project teams, design and develop an engineering system addressing a real-world problem. Projects are based on themes addressing most pressing needs of human society; for 2017-2018 the theme is clean energy. **Learn and utilize industry development process;** first quarter focuses on establishing requirements and narrowing to top concept. Second quarter emphasizes engineering analysis, design **risk assessment**, build, **test and iteration**. Learn and apply professional communication skills in the areas of speaking, presenting, writing, and listening.
Purdue	*ME 45200 - Machine Design II* Design and analysis of mechanical systems, for fluctuating loading. Fatigue analysis. Application of design fundamentals to mechanical components, and **integration of components to form systems. Design risk assessment, build, test and iteration**.
Penn State	*ME 340: Mechanical Engineering Design Methodology* The design process, problem definition, conceptual design, **system design**, detail design, **evaluation and test**, **implementation**, **documentation** and communication
University of Wisconsin	*M E 445 — Mechatronics In Control & Product Realization* The course will cover fundamentals of electromechanical control systems with a focus on **subsystem design impacts at the system level**. Students will learn how to **integrate** microcontrollers into products for control and/or instrumentation and learn how to create intelligent **interfaces** *M E 351 — Interdisciplinary Experiential Design Projects* First of a two-course sequence in which students design and fabricate **systems** and devices, typically having an i**nterdisciplinary** aspect. In the first course, emphasis will be on project planning, team dynamics, problem identification, and conceptual design and evaluation. *M E 352 — Interdisciplinary Experiential Design Projects II* Second of a two-course sequence in which students design and fabricate systems and devices, typically having an **interdisciplinary aspect**. In the second course, emphasis will be on detailed design, fabrication, **testing**, and modification of concepts developed in the previous course.
Georgia Institute of Technology	*ME 4803 M- **Model Based Systems Engineering***

Table 32 (con't)

Institution	Systems-Related Courses
California Institute of Technology	*CS/EE/ME 75 abc. Multidisciplinary* ***Systems Engineering*** This course presents the fundamentals of modern multidisciplinary **systems engineering** in the context of a substantial design project. Students from a variety of disciplines will conceive, design, implement, and operate a system involving electrical, information, and mechanical engineering components. Specific tools will be provided for setting project goals and objectives, **managing interfaces between component subsystems**, working in design teams, and tracking progress against tasks. Students will be expected to apply knowledge from other courses at Caltech in designing and implementing specific subsystems. During the first two terms of the course, students will attend project meetings and learn some basic tools for project design, while taking courses in CS, EE, and ME that are related to the course project. During the third term, the entire team will build, document, and demonstrate the course design project, which will differ from year to year.
Virginia Tech	*ME 4015-4016: Engineering Design and Project* Team oriented, open-ended, **multi-disciplinary** design projects focused on industrially relevant problems. A specific**, complex engineering design problem** is normally taken from **problem definition to product realization and testing**. Emphasis is placed on **documenting and reporting** technical work, idea generation and **selection**, application of design and analysis tools developed in previous courses, **project management**, selling technical ideas and working in teams.

Purdue's Machine Design II includes the integration of components into systems. Stanford's Mechanical Engineering Design--Integrating Context with Engineering covers industry development processes and design solution testing and iteration. Pennsylvania State University's Mechanical Engineering Design Methodology course includes system design, evaluation and testing, implementation and documentation. One of the University of Wisconsin's technical electives in mechatronics includes a focus on product realization and covers "subsystem design impacts at the system level" and learning "how to integrate microcontrollers into products" and "create intelligent interfaces". This is very unique and interesting to see that a very technically specialized course includes elements of systems engineering principles. Also to note is this institution's senior capstone design is titled "Interdisciplinary Experiential Design Projects". While not including the word "system", systems engineering is inherently interdisciplinary and involves the coordination of various disciplines, so one could interpret a broader coverage/consideration of design by the title. Georgia Institute of Technology has a Model Based Systems Engineering technical elective, however it isn't clear when it was last offered and no description is available. California Institute of Technology offers a Multidisciplinary Systems Engineering course as one of three optional design capstones. Students in this course are from several engineering disciplines and work together to "conceive, design, implement, and operate a system involving electrical, information, and mechanical engineering components" and "managing interfaces between component subsystems". This institution also describes the field of mechanical engineering as one that "emphasizes the process of formulation, design, optimization, manufacture, and control of new systems and devices."

It is important to note that for each program systems engineering concepts are included in an upper level, design-based course, most of which are the senior design course. All of the programs listed have a senior capstone design course; however, not all take the design process further to include integration into the larger system and systems thinking, based on the course descriptions. The design aspects of systems engineering seem to be, at least, introduced, but coverage of systems concepts, system implementation and operation are missing. No systems verbiage is included in first or second year course descriptions.

5.3 Curricular Integration

As shown in the reviews of literature and mechanical engineering curricula, systems engineering concepts, when included in a curriculum, are most commonly found in a senior year design-based project course. This is narrowly focused on the design process and the approach to defining "what" then attempting to solve "how". A systems approach goes beyond the initial problem definition to consider the entire product life cycle, to include testing, production, system support (reliability, maintainability), system operation (safety, human factors) and disposal. Systems thinking also considers how this design interfaces and operates with other components in the overall system [5]. With this limited focus on steps in the design process, many students do not understand the context of their design in the overall system life cycle and do not fully appreciate the value of such a tedious design methodology [1]. These considerations are critical, most especially in large, complex systems, developmental projects and life cycle engineering, found in virtually every industry.

Therefore a program level, or system level, approach to curricular inclusion is taken. Using information learned from the survey regarding important systems engineering concepts and existing inclusion of such concepts in mechanical engineering undergraduate curricula, this section describes a method to incorporate systems engineering into a mechanical engineering undergraduate program. Program-level student learning outcomes are defined, faculty interviews are summarized, and courses for systems concept inclusion are identified.

5.3.1 Program Level Outcomes

This research takes a top-level curricular approach at the program level. Thus taking systems engineering competencies from a high-level perspective, related program level student learning outcomes are created. This provides a framework from which curricular adjustments can be made and student learning can be assessed. The outcomes are meant for inclusion in a mechanical engineering curriculum, but they are stand-alone and can be included in any curricula. Performance indicators are defined with associated minimum and desired levels of achievement. Each outcome component is traced to a need: a systems engineering competency identified in the survey. Indicators related to the new ABET criteria are also traced. These are composed into a rubric following the style of the Association of American Colleges and Universities (AAC&U) VALUE rubrics [65]. VALUE stands for Valid Assessment of Learning in Undergraduate Education.

Two program level student learning outcomes are established based on the identified systems engineering competencies needed in mechanical engineering undergraduate curricula. The first learning outcome is Engineer Complex Mechanical Systems, and the rubric is found in Table 33. This involves the ability to define a component, sub-system, system and system of systems and further describe their relationships. The majority of systems engineering competencies are included in this outcome. The second learning outcome is Design Complex Mechanical Systems, and its rubric can be found in Table 34. Inclusion of systems engineering concepts in the design process is the focus of this outcome. Most mechanical engineering curricula include a senior design course; however, the level of focus on systems concepts may vary widely across institutions and even among instructors. This level of course detail is not widely published, therefore, it is included here. This outcome ensures the system lifecycle, user and stakeholder are considered in the design process in addition to concept generation, solution selection and technical aspects of design.

Upon further discussion of the stated performance levels at graduation, a revision is recommended. Feedback suggests a significantly large gap between the minimum level and desired level at graduation. It is possible the minimum level is too basic; however, further research must be conducted to determine appropriate levels.

Table 33: Engineer Complex Mechanical Systems Rubric

LEARNING OUTCOME:		OUTCOME DESCRIPTION:		
Engineer Complex Mechanical Systems		Define and describe the stages of and relationships between a component, sub-system, system and system of systems.		
	Component	**Desired Level at Graduation**	**Minimum Acceptable Level at Graduation**	**Traced to Systems Engineering Competency**
a.	**System-Level Thinking**	**Contextualize** designed component or sub-system within the overarching system concept and operating environment (system of systems). *(explain relationships among them)*	**Recognize** designed component or sub-system within the overarching system concept.	System Concepts; System of Systems; ABET Student Outcome Criterion 3.1
b.	**Dealing with Complexity**	**Describe** the system hierarchy. **Apply** theory and techniques to simplify complexity (solve complex problems).	**Identify** the system hierarchy. **Recognize** theories and technique to assist with addressing complexity.	System Concepts; ABET Student Outcome Criterion 3.1
c.	**System Boundaries and Interfaces**	**Categorize** system/sub-system/component boundaries and interfaces. **Create** related formal documentation.	**Identify** system/sub-system/component boundaries. **List** associated documentation.	System Concepts
d.	**System Lifecycle**	**Explain** stages of a system/sub-system lifecycle.	**Identify** stages of a system/sub-system lifecycle.	System Concepts

Table 33 (con't)

LEARNING OUTCOME:		OUTCOME DESCRIPTION:		
Engineer Complex Mechanical Systems		Define and describe the stages of and relationships between a component, sub-system, system and system of systems.		
	Component	**Desired Level at Graduation**	**Minimum Acceptable Level at Graduation**	**Traced to Systems Engineering Competency**
e.	**System Implementation**	**Analyze** processes and considerations for integrating a component/sub-system into the super system.	**Recognize** activities required to transition the component/sub-system to its operational environment and system.	Transition to Operation; Integration
		Formulate high-level testing approach to verify and validate design solution. **Create** related formal documentation.	**Identify** the need to verify and validate solution. **List** associated documentation.	Verification; Validation (Testing)
f.	**System Management**	**Employ** methods to trace design solution to stakeholder needs and technical requirements. **Identify** related formal documentation.	**Explain** need to trace design solution to stakeholder needs and technical requirements.	Requirements Management
		Create configuration documentation; **Identify** change control processes.	**Explain** the need to document changes to design solution.	Configuration Management
g.	**Multi-disciplinary Teams**	**Coordinate, communicate** and **function** on multi-disciplinary teams.	**Identify** sub-specialists and other engineers that can play a role in a complex system.	Integration of Specialties; ABET Student Outcome Criterion 3.5

Table 34: Design Complex Mechanical Systems Rubric

LEARNING OUTCOME:		**OUTCOME DESCRIPTION:**		
Design Complex Mechanical Systems		Incorporate systems engineering concepts into the design process to ensure design solution meets the stakeholder needs and considers the system lifecycle and user.		
	Component	**Desired Level at Graduation**	**Minimum Acceptable Level at Graduation**	**Traced to Systems Engineering Competency**
a.	**System Design**	**Translate** stakeholder needs into requirements and technical specifications. **Create** related formal documentation. **Identify** connection between requirements and system implementation stage.	**Identify** stakeholder needs. **Define** requirements.	Stakeholder Expectation; Requirements Analysis; Technical Specifications
		Apply Human Factors Engineering *(usability theories*) in the design process.	**Recognize** the need to consider the user in the design process.	Design Considerations for "-ilities"; ABET Student Outcome Criterion 3.2
		Evaluate solution concepts through a formal process by **applying** appropriate tools and techniques.	**Identify** criteria for evaluating design solutions.	Decision Analysis
		Evaluate potential risks of design solutions. **Create** risk mitigation strategies.	**Identify** forms of risks.	Risk Management; System Robustness; Evaluate Solutions
		Incorporate lifecycle considerations ("-ilities") into design solution.	**Recognize** constraints that could affect the design.	Design Considerations for "-ilities"; ABET Student Outcome Criterion 3.2

5.3.2 Faculty Perspectives to Curricular Inclusion

Interviews with faculty at one institution are conducted to glean feedback on the program outcomes, the relevance of incorporating them in a Mechanical Engineering curriculum and some ideas on how (methods) and when. The following positions in a mechanical engineering undergraduate program were interviewed: an undergraduate program director, an associate department head, and a senior capstone design course coordinator. A director of first year engineering was also interviewed for a perspective on inclusion in the first-year common engineering coursework.

The first-year engineering director, Anthony Cahill, is a civil engineer and oversees the curriculum and content of the first-year engineering courses common to all engineering students. He mentions use of systems engineering concepts in the civil engineering industry, specifically in the area of water resources. Systems concepts are important and valuable, but he questions how to fit them in an already constrained first year curriculum. He suggests incorporating two lecture modules on systems engineering in the first year and points out that some aspects are already included when teaching the design process. Also, the problem-solving process involves identifying the system of interest and its boundaries and, specifically in conservation laws, considering what crosses these boundaries. So, in some ways "systems" are already covered or at least introduced. The author adds that it may be a matter of tweaking the content and relating concepts to systems engineering and other applications as well as planting the seed for future exploration of these concepts.

The mechanical engineering undergraduate program director, Matilda McVay, is excited about this idea. She envisions inclusion of these concepts in any or all of the three design-related courses in the curriculum at her institution. The curriculum has a two-semester senior capstone design course sequence in which the design process is introduced and a higher-level approach to a problem is taken. She points out that House of Quality is also taught. A third design-related course involves experimentation in which the students identify a problem and design an experiment to solve it. She states that some of the systems engineering learning outcomes could be met through incorporation of the competencies within the course content. First-year courses is another good place for inclusion, she states, especially in the introduction of teams. One consideration is how to introduce this at the freshman level versus at the senior level.

Joanna Tsenn, the senior capstone design course coordinator, confirmed most of the systems engineering indicators in the rubric are already included, at least in an introductory level, in the two-semester senior design sequence. System implementation is not included in the courses. Two areas she observed that students struggle with are working in teams and system integration. Regarding teamwork, she has observed difficulty in communication between students of different engineering disciplines. Some senior design projects include non-mechanical engineering majors on the team. Students in other disciplines speak a different language (discipline-specific terms) causing difficulties when working together. Another challenging aspect of teamwork observed is the students' approach to task completion. They tend to actively work on tasks together rather than divide tasks among team members and then come together to integrate individual parts in the end.

In terms of system integration, she has seen mechanical engineering senior capstone design projects becoming more complex over the years. Gone are the days of single component design and fabrication. Current projects could have a team of up to six students who divide the project into three or four areas. The teams have trouble at times identifying needs and defining requirements at the system level. They have difficulty understanding the hierarchy of a system and how subsystems and components come together to form the system. No team leader or system integrator is assigned. The students can get confused in regards to meeting stakeholder needs at all levels of the project and design solution.

Arun Srinivasa, associate department head, is involved in curricula and course re-design efforts as well as engineering education studies. He has a devoted interest in these topics and many ideas on how to improve the educational experience for mechanical engineering undergraduate students. From a program level perspective, his approach to educating mechanical engineering students is as follows: in the first year, students learn how to learn, what engineering is, and how to define a system as a simplistic representation detached from its environment (define boundaries); in the second year, students learn concepts and focus on discovery; in the third year, students learn tools of evaluation (courses are very technical); in the fourth year, students apply what they have learned and create something through the action of design. Several of these systems engineering concepts are included in existing courses in the curriculum, mainly those courses focused on design. They could be woven into existing technical electives. The key approach to a system is its interfaces. Students have a difficult time separating a system from its surroundings and simplifying it in order to approach it from an engineering and scientific perspective.

5.3.3 Suggestions on Curricular Inclusion

The aim of this research is to ensure students develop a systems-thinking mindset and are prepared to function in a systems-oriented work environment through the application of systems engineering competencies. The survey indicates most graduates do not use systems engineering concepts within the first few years of graduation. A benefit of systems engineering knowledge to mechanical engineering graduates is in their career progression to leadership roles in project management or as a chief engineer or in some cases a systems engineer. Another common comment by survey participants is the variety of systems engineering vernacular used among different companies and industries. These data points support the following approach to curricular inclusion: 1) systems engineering concepts must be taught as a way of thinking, not solely as a set of processes to follow 2) the concepts must be woven throughout the curriculum and built upon each year. Most importantly, systems engineering and systems thinking must be valued at the program level. Program objectives and mission statements should include systems verbiage which guides the entire program as a whole. Each particular institution must determine how best to weave systems concepts into its program based upon its unique perspective and language.

Concepts from systems engineering are sometimes borrowed for instruction of a formal design process in the mechanical engineering senior capstone course. This is narrowly focused on the first stage of establishing design criteria through the process of defining “what” is needed before attempting to solve “how”. A systems approach goes beyond the initial problem definition to consider the entire product life cycle, to include testing, production, system support (reliability, maintainability), system operation (safety, human factors) and disposal. Systems thinking also considers how this design interfaces and operates with other components in the overall system [5]. With this limited focus on steps in the design process, many students do not understand the context of their design in the overall system life cycle and do not fully appreciate the value of such a tedious design methodology [1].

From a high level perspective on a mechanical engineering curriculum, the researcher suggests inclusion of systems engineering concepts throughout the program. Based on survey data and a review of existing mechanical engineering curricula, a limited number of systems concepts are currently included in senior year design courses. Much of the focus relates to the design process with some discussion of integration and implementation. Design courses can be tailored to meet the Design Complex Mechanical Systems and Engineer Complex Mechanical Systems learning outcomes focusing on the desired level of performance at graduation. The senior capstone design course is meant to recall knowledge previously attained and contextualize it in a real world application to solve a complex problem. Systems engineering concepts need to be introduced early in the curriculum.

Approaches to systems engineering education have been discussed at previous ASEE Annual Conference Systems Engineering Division (SED) workshops. In 2017 the focus was on inclusion of model-based systems engineering in the senior capstone course; however inclusion in first year courses and a summer grand challenge project were also presented. There is agreement that the senior year is too late for first time exposure to systems engineering and systems concepts. Workshop participants and feedback from students at their respective institutions express the need for introduction in the first year and building upon this foundation in subsequent courses. In order to create a mindset of systems thinking, the concepts should be reinforced and then synthesized in the senior year.

Workshop presenters state that first year engineering students are generally taught the essence of engineering thinking and design approach: understand “what”, brainstorm “how”, analyze alternatives, and select a solution. They suggest educators incorporate systems thinking into existing design processes. Starting with the “what”, the following questions can be asked: what are we doing? What is the problem? Then use these questions to introduce the concept of requirements definition. Then ask: What is the desired end result? Use this question to introduce the concept of the system life cycle. If the end result is a product, there are multiple stages to get to a finished product and multiple stakeholders involved in order for the product to exist, ie. finance, sales, marketing, manufacturing, distribution. The engineer must consider more than just the technical aspect of design but the entire system the design solution functions within and the contributing parts to product realization. The first year engineering course is an ideal setting to introduce systems concepts and approaches without the technical focus.

Another poorly understood step in the problem definition stage is translating stakeholder needs, according to workshop presenters. Customers may think they know what they want and sometimes what they ask for includes a partial solution. The customer may also not see how their part fits within an overarching system. It is the job of the engineer to properly define the customers’ needs and translate them into requirements, considering external interfaces and system integration. Students can learn through an exercise that progresses them through a design process with poorly defined stakeholders’ needs leading to a solution that doesn’t integrate into the overall system. Students can then be taught the proper approach and additional system level considerations and re-work the exercise.

In addition to the design approach, first year coursework generally introduces students to the discipline of engineering, the process of problem solving and tools to solve engineering problems.

This is an ideal setting to introduce the concept of a system, defining a system, system hierarchy and system boundaries and interfaces. The idea that engineering is not only design should be introduced, discussing the other considerations of a product, part or system once produced and in operation. Methods of functioning on teams and the importance of communicating between sub-teams can be demonstrated through an activity requiring the integration of output generated from several sub-teams to create a functioning system or solve a problem. These are foundational concepts to be learned by the student which can be built upon through subsequent courses. First year engineering learning outcome components include: system design, system-level thinking, system boundaries and interfaces, system lifecycle and multidisciplinary teams.

Most mechanical engineering curricula include a computer-aided design (CAD) course, introducing students to design, fabrication and software tools. This is an ideal course to introduce system design, system-level thinking, system boundaries and interfaces and system implementation. Students are introduced, or re-visit, the design process. Systems engineering elements can be infused by placing an emphasis on identifying the stakeholder, stakeholder needs, and integration considerations (how the component being designed fits into the overall system). Other topics to include are: identifying and defining interfaces between the component and the system and the component/system and the user; an introduction to validation and verification.

Universal mechanical engineering courses at the sophomore and junior level that can be tweaked to infuse systems engineering concepts: thermodynamics, statics, dynamic systems, fluid dynamics, heat transfer, machine design. As mentioned by one faculty member, systems and system boundaries are presented in the discussion of conservation laws. This is an opportune time to further discuss the definition of a system, its boundaries, and its context within a larger system (system hierarchy and interfaces). The idea is to take a systems approach in teaching these fundamentals to introduce students to systems concepts and develop a systems perspective. From this view, content is delivered in a way that guides students to view a single part or component or mass as a unit in a larger system and understand how the various parts of a system relate to each other.

A common response in the survey is to offer an elective course in systems engineering. If the mechanical engineering curricula is adjusted to incorporate systems engineering concepts throughout the program, then an advanced elective course on systems engineering tools and methods could be offered. One or two learning outcome components could be explored to a higher level of Bloom's taxonomy [66]. One such course combines system design and dealing with complexity. Topics include: advanced tools for decision making and optimizing the design solution, defining complexity and how to simplify complexity. Students would be expected to conduct analysis using provided tools and evaluate results. Learning outcome components covered are: system-level thinking, dealing with complexity, and system boundaries and interfaces.

Senior design courses often focus on the detailed, technical design solution and negate the system perspective. To address this, a senior capstone design course utilizing a large, complex system for the design problem could be offered for students interested in gaining experience on such a project. Teams are composed of sub-teams that must work together to integrate each part into a whole, system solution. Technical management roles are needed to track and document requirements and progress of each sub-team, to facilitate communication, and to document interfaces. Each team must understand how their part fits within the hierarchy of the system and how a change to their component affects the larger system.

Challenges to curricular inclusion include: awareness by administration and faculty of the need to incorporate systems engineering concepts in the curriculum, faculty expertise in systems engineering, constraints in the curriculum and student intellectual maturity. The proposed method could require a level of systems engineering knowledge by all mechanical engineering faculty. If these new concepts are incorporated into existing courses, the faculty teaching these courses must understand systems engineering in order to incorporate into their course. One possible solution is to hire faculty with knowledge of systems engineering to develop the first year course and the design-based courses, since these have the most flexibility for inclusion of systems engineering. They could also develop systems engineering-based electives, assist with incorporation of system engineering in traditional courses and possibly guest lecture. Mechanical engineering degree programs are constrained by credit hours and existing learning outcomes. It may be challenging to add additional content to courses. In regards to students' intellectual maturity, they may have difficulty comprehending the abstraction inherent in systems concepts. In addition, without a proper context, they may struggle with relevance.

6. SUMMARY AND CONCLUSIONS

A graduate of a mechanical engineering undergraduate program should not be expected to perform duties of a systems engineer. Most systems engineers assume that role after years of engineering practice. However, the point is that familiarity with systems engineering concepts and methods and approaching engineering with a systems perspective is necessary, most especially with the ever-increasing complexity of systems in our world today. Feedback from mechanical engineering graduates point to this conclusion. A survey was distributed to graduates with a Bachelor of Science degree in Mechanical Engineering. Data shows that most respondents execute systems engineering competencies in their job and most recommend inclusion of systems engineering concepts in the undergraduate mechanical engineering education. Existing undergraduate mechanical engineering programs do not fully integrate systems engineering concepts in their curriculum. A limited number of programs offer select courses with a systems engineering approach, most of which are the senior capstone design course. Systems engineering expands well beyond the design process. It is a way of thinking and approaching engineering problems and managing operating systems. Therefore, it is proposed that systems engineering be placed in prominent importance at the program level by infusing systems engineering concepts throughout the mechanical engineering curriculum. Program level learning outcomes for systems engineering are defined and an approach for curricular inclusion is presented. Faculty perspectives on systems engineering in a mechanical engineering education are also shared.

7. FUTURE RESEARCH

This research effort has identified areas of systems engineering that are essential for undergraduate mechanical engineers to learn. Further study into correlations between years of experience and systems engineering preparation may be of interest. Respondents with less than six years of experience indicate a slightly higher percentage of learning concepts in their undergraduate education than those with over thirty years of experience. This may be a result of changes to the curriculum over time. Those with more experience indicate a slightly lower percentage of "yes" recommend inclusion in undergraduate curriculum. There is also slightly more distinction between the competency levels "none" and "able to execute" than with the less experienced respondents.. Refinement into specific systems engineering competencies used and recommended for inclusion based upon experience level could also be explored. The correlation between job title and when specific competencies are used and to what level they are used could also be investigated further. In addition, the majority of participants are from a single institution. There are inherent biases towards their undergraduate experience and preparation for their career. A broader perspective can be gathered in future studies by surveying graduates from multiple institutions. Finally, based on respondent comments, a poor explanation of systems engineering was given in the survey introduction. Many respondents opted out of participating with the reasoning that they do not know what systems engineering is and/or don't think they have used such concepts. Participants were able to move forward and preview the survey before opting out. It is possible that a different approach to the survey invitation and introduction could elicit more complete survey responses.

Science continues to advance and as systems become increasingly complex and autonomous, approaches to engineered solutions must also evolve. The field of systems engineering recognizes this need and the SERC is working towards solutions. One such example is a system of humans and electronic devices working together to perform a task while allowing other systems to connect/disconnect and the entire system can adapt to a changing situation [67]. This type of system is known as an adaptive cyber-physical-human system. Researchers continue seeking methods and tools to properly design and model such a system that captures the integrated dependencies and relationships among the subsystems.

Systems are becoming increasingly driven by software and advanced networking capabilities with data exchange among subsystems, components and humans. This is especially prominent in autonomous and adaptive systems. Adaptive systems learn as they execute and can react to a new, unknown situation. One important question for a systems engineer is how to document and track such a system and ensure proper communication and interfacing with other systems [68]. Groups of autonomous devices working together for a common objective is an example of subsystems working collaboratively and machine learning taking place. As systems advance, there must be ways to approach design of such systems (how does the designer write requirements for such a system), document (model) the solution and the evolving configuration, and plan for interfaces with other systems and integration into the super system. In addition, how does one verify and validate such a system that is constantly evolving?

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APPENDIX

Survey – Invitation to Participate

Email Request to Complete Survey- sent to former students

Dear ,

As a graduate of the department of mechanical engineering, we are seeking information regarding your career experiences. Specifically, we are investigating systems engineering concepts that are used by graduates of mechanical engineering. We kindly request your participation by completing a questionnaire at the link below. If you don't think your experiences are relevant, please indicate accordingly on the first page of the survey. This is very useful data and will skip the remaining questions. However, you are still encouraged to participate as systems engineering concepts are widely used across many fields. You do not need to be familiar with specifics of systems engineering to complete the survey. The questions will ask about specific competencies (definitions are provided).

The survey will be open through January 10, 2018, and should take no longer than 20 minutes to complete. Participation is completely voluntary, and all responses will remain anonymous; no identifying information will be collected.

Please feel free to share this public link tx.ag/MEEN with graduates of other undergraduate mechanical engineering programs.

Thank you for your participation in this effort.

Email Request to Complete Survey- sent to colleagues

We are investigating systems engineering concepts that are used by graduates of mechanical engineering. The objective is to show whether or not systems engineering concepts should be included in mechanical engineering undergraduate curricula, and if so, which concepts and to what level of understanding. We kindly request your participation by completing a questionnaire at the link below. It should take no more than 20 minutes to complete and responses are anonymous. Participation is completely voluntary.

Survey Landing Page

Systems Engineering Concepts Important for Mechanical Engineers

Information about this study: The objective of this questionnaire is to survey graduates of a mechanical engineering undergraduate program regarding their exposure to and use of concepts within systems engineering. Mechanical engineers work in a wide variety of jobs upon graduation, some in non-engineering functions. Thus your input truly is important, regardless of your chosen career path. While systems engineering has many interpretations, this survey breaks it down into industry-identified competencies. You will be asked to answer several questions regarding each competency based on your work experience. This survey is part of a research study investigating concepts of systems engineering used by mechanical engineers and how to teach them in an undergraduate mechanical engineering curriculum. Results of this survey may inform future curricular revisions and may be published, without any identifying information. The survey should take no longer than 20 minutes to complete. Participation is completely voluntary, may be ended at any time, and all responses will remain anonymous.

If you have any questions regarding this survey you may contact the research team:
Graduate Research Assistant: *Rachal E. Thomassie*, rthomassie@tamu.edu
Principal Investigator: *Dr. Timothy J. Jacobs*, tjjacobs@tamu.edu
Department of Mechanical Engineering
Texas A&M University, College Station, TX 77843

Q20 In what industry has the majority of your career been?

____

Q36 How many years of work experience do you have?

____

Q22 What is your current job title?

____

Q37 Have you ever performed in a Systems Engineer role?

- ◯ Yes
- ◯ No

Q23 Do you have formal training or education in systems engineering?

- ◯ Yes
- ◯ No

Q24 What type of training?

- ◯ University degree (undergraduate or graduate)
- ◯ Certificate or minor (college or professional)
- ◯ Employer Training Program

○ Other ____

Q31
<OPTIONAL>
I prefer not to continue because (choose all that apply):
NOTE: After selecting one (or more) of the following, click NEXT to record your response and end the survey.

- ☐ I do not think I have used systems engineering concepts in my job(s)
- ☐ I have not worked as a practicing engineer
- ☐ Insert your reason: ____

Survey Demographics

Table 35: Participant Industry Experience

Industry	%	Count	Industry	%	Count
Petroleum/Oil&Gas	26.5%	380	Electronics	0.8%	11
Manufacturing	6.6%	95	Consumer Goods & Products	0.8%	11
Aerospace	6.1%	87	Aviation	0.8%	11
Chemical	5.1%	73	Technology	0.7%	10
Energy	4.3%	62	Research/Academia	0.7%	10
Defense	4.0%	57	Medical	0.7%	10
Petrochemical	3.5%	50	Facility/Building System Design	0.6%	9
Construction	3.5%	50	Computers	0.6%	9
HVAC	3.3%	47	Facility Operation/Management	0.6%	8
Automotive	2.4%	34	Government	0.5%	7
Law	1.9%	28	Food	0.5%	7
Consulting (Engineering)	1.9%	28	Business	0.5%	7
Utilities (water or power)	1.7%	25	Transportation	0.4%	6
Refining	1.7%	25	Agriculture	0.4%	6
Semiconductor	1.6%	23	Pulp and Paper	0.3%	5
Bio/Medical Devices	1.6%	23	Turbomachinery	0.3%	4
Power Generation	1.5%	22	Religious	0.3%	4
IT	1.5%	21	Real Estate	0.3%	4

Automation/Controls	1.3%	19	Pipeline	0.3%	4

Table 35 (con't)

Industry	%	Count	Industry	%	Count
Software Development	1.1%	16	Packaging	0.3%	4
Finance	1.0%	14	Metals	0.3%	4
Education/Teaching	0.9%	13	Insurance	0.2%	3
Telecommunications	0.8%	12	Civil Engineering	0.2%	3
R&D	0.8%	12	Data	0.1%	2
Project Management	0.8%	12	Pharmaceutical	0.1%	1
Nuclear	0.8%	11	Other	2.6%	37

Section 1- Systems Thinking Area Free Response

The following are text responses entered by participants when prompted for comments regarding the listed competencies in this area. No edits to the text have been made.

My experience with systems integration has largely been from an IT perspective

In my work experience, "systems engineering" is a meaningless buzzword. People claiming to be "systems engineers" do nothing other than what anyone else woudl do.

Much of what I learned on the job came from my co-op job experience.

The type of Systems Engineer that I am is not IT related. It is an overall Technical Manager for a large offshore project, where Subsea Equipment is integrated into a larger "system" of equipment (valves, pipe, manifolds etc) that transports that crude oil from the well under the sea, up to the platform. So I dont think that this quiz is applicable to me.

Very confusing questions and wording of the questions. For example, "Enterprise Engineering" could have many meanings.

There are no definitions for these skills and I am not a Systems Engineer so I can't answer these questions. Typically engineers that integrate multiple processes are called process engineers.

In our industry, electrical engineers that chose the Instrumentation and Controls path are sometimes the "Systems Engineers".

I believe learning on the job is the best way to learn these concepts.

Don't understand the above wording - I have worked as a senior project engineer for 20+ years integrating multi-engineering disciplines from conceptual stage to construction. As part of that work, it includes the integration of computer systems to operate the plant safely. This was mainly learned on the job at Dow Chemical. When you ask would you recommend it to be included, maybe. There are professional PMI courses in the industry and really you need the job background before they become relevant and beneficial. They may be beneficial for those that has co-op and have seen industry.

The survey should provide a general definition of all request fields. The survey leaves definitions open to interpretation and could result in poor survey results

I'm giving my feedback based on the description rather than the label. "Able to execute" is a little squishy... I have done projects that fit the stated description but I have some doubt that my "execution" would align with a formal "Systems Methodology". That said, the projects certainly were completed.

I've no idea what any of these terms mean. I'm fairly sure that I have worked with systems, just don't know the formal terminology

I work on control systems and it is important for our engineers to understand the processes that are adjacent to the equipment our systems control. For instance an engineer working on our anti surge controls needs to understand the interaction with the process controls governing the compressor throughput.

I was blessed to work with Dr Lalk, and the foundation in my ME design class allowed me to work as an intermediary between the ME and the EE/Controls teams. Without Systems Engineering I would not have been as successful.

I need definitions of terms in the left column. I probably have experience in the areas listed.

In my opinion, undergraduate curriculum should focus on learning fundamentals. Once those concepts are well understood, a systems thinking approach can be applied.

I think the value of learning systems is learning the systems specific to the industry and role taken. So I think that classes which may expose students to different industries and their concepts should include a systems as part of the curriculum.

Enterprise and Technology Environment is very important. I'm in the process of specing out a software system at work. I think this and the interactions with other departments should be taught in an ME UG curriculum.

The fact that this is being surveyed is awesome. However, I believe most engineers will have little understanding of systems engineering and may answer inappropriately. Keep in mind that a job search for system engineer turns up IT positions.

None

not sure what they mean, but I was the lead eng on a satellite project and we had a lot of systems to integrate.

Essentially everything we do can benefit from systemizing, including documentation, roles/responsibilities, methodolgy, supporting technology, training, verification/audits/accountability, etc., etc., etc. So, it is somewhat unclear just what you all mean by systems. It was to be done to some level by essentially everything from McDonalds to Boeing, to ExxonMobil and so on.

None

not sure abou the question on when did I use this concept - is that when I last used it OR how long have I used it?

For the major international, billion dollar projects engineered by my former employer, systems engineering was an integral part of every successful project. It was likely the most challenging part of training for any new graduate or any new employee. Most have a good understanding of working in teams, but the specifics of systems engineering was not inherent in their educations or experience.

Enterprise Architecture is a term I've used/heard a lot that is very related to System Engineering

My experience is in power, refineries, and chemical plants. The integration of systems requires one to be a generalist in the whole and a specialist in the item integrated.

I am in medicine but do often apply systems concepts when I am working on how my office works and how it interacts with other offices and with hospitals.

Enterprise Integration to me is associated with Systems Architecture and Software - I'm not sure if that's how you intend for people to receive it here.

"Systems Concepts" needs more clarification.

A spacecraft must be regarded in the context of a system of systems due to inherent complexity and the the network of systems required to support it.

Able to Execute contains a wide-variety of possible exposures and capabilities - would prefer a numerical scale here to gauge competency (more typical of skills and experience matrices we fill out for competency in my industry

This survey should have started with a definition of what you mean by Systems Engineering. My comments are based on components such as Reliability, Maintainability, Operability, Safety, Optimization, Testing, Commissioning, Risk Management, etc.

I think a lot of the terms above are used only in certain ways industries.

The language used here is unfamiliar to me, but the concepts described are relevant to our engineering work.

Have probably applied the concepts without knowing it. Not familiar with the vernacular.

My primary job function began in operations management. Later assignments in start-up of new processes and systems gave exposure to systems concepts.

Maybe some examples would be helpful - the descriptions are very generic, but I believe they are related to my experiences.

Understanding the nature of Systems and Systems of systems helps an engineer to design and think in terms of compatibility with the work of others. In the work environment, one quickly learns that great ideas that cannot link up with other ideas are all but useless.

Please note that the majority of my work experience has been as a government acquisitions program manager, not as an engineer per se. Systems Concepts throughout education.   Enterprise and technology environment, first and last year. Systems of Systems as a specialized course and as a portion of system concepts. Remaining, mentioned in systems concepts and really taught last 1-2 years.

None

Systems Concepts are important to understand, but you need to know too munch about too many things to have an education on Systems, Enterprise and Technology, Enterprise Integration or Integration of Specialties mean anything at an UG level. My ability to Execute came after 20 years of experience in multiple parts of the oil and gas industry.

We live in a data driven environment. Our data is collected, manipulated and reported out though various systems. This is a great skill engineers to develop. It is mandatory if one wishes to move into management.

Senior Design projects that bridge engineering disciplines should provide substantial opportunities to practice systems engineering at the undergraduate level. I do believe that for the most part these skills are obtained by being part of large projects requiring many engineering disciplines. Also years of experience is required to understand and develop a vision for how to best integrate large multidisciplined design features.

Appreciating other sub disciplines and systems thinking is critical and the foundation should be laid in undergrad. More academic time devoted to interfacing with enteripirise systems and other business functions is important but should not take away from learning core eng discipline skills. This can be learned better through experience in student organizations such as the MSC.

I have been working on how Honda does new product development and systems engineering has been one of our discussion areas.

Do not think that this has value at this level of education. Appreciation comes after years of experience.

Systems engineering is very unique to the company and the integrated product offering. So much of the training and concepts are company specific, and get built on experience and the ability to lead a group of technically competent individuals.

My experience is in subsea systems engineering in the oil and gas industry. Design of subsea production systems.

I am not familiar with these terms. My role as a systems engineer is specific to the industry I work in and it refers to the group that lead the development of Piping and Instrument Diagrams (P&IDs) for the design of Oil and Gas facilities / projects.

you are using "college speak", most industry would not recognize the terminology used, certainly not management that is in their 50's to 60's.

Not sure what the formal titles in the left hand column represent exactly but feel that all graduating ME's should be aware of how what they do integrates into company goals, products, and customer needs. My opinion is that these systems vary widely from organization to organization as well as with product fields so the job environment is the most effective teacher of the detailed systems but a basic integration education should be understood before graduation.

A few of these topic very widely between companies and would be difficult to teach in course work. For example, the role that HR or Health and Safety take in different companies and their level of responsibility for a system could be vastly different even between two companies of the same size within the same industry. I believe that trying to teach this through course work and not no-the-job experience could detract from other course work and key engineering concepts studied.

I also developed solutions for an aerospace company at approx 2 billion savings.

Enterprise Integration is usually done by the IT group and not Engineering.

Please provide some "real-world" examples of types of systems. Based on my experience, I made some assumptions regarding the definition of a system. We use terms such as process or work flow that I interpreted as your definition of system. We still use the term system, but it is reserved for more traditional examples, such as a hydraulic system for a compressor. As to being included in future curriculum, I think all ME graduates would benefit from exposure to these concepts. Application of the learning will come later in their careers though. There is no substitute for real-world experience.

Systems design becomes multidisciplinary, and it varies dramatically depending on industry. Also, I dont think it is teachable. Creativity is required. Additional note, "system of systems", "enterprise integration", "integration of specialties", This is a fine set of gobbledygook.

Systems Engineering definitions also includes the management side of planning, integrating resources, managing performance (earned value), risk management, and closure.

My years of experience were not based on some governmental model but real life experiences. It probably fits one of the models but not specifically. Based on the young engineers i have seen in my career of working with them hiring them they have no concepts of systems. It should be taught.

I am not familiar with most of these terms, which makes me think they should be included in ME curriculum

I like the term Large Scale System Integration as I think it is more descriptive than System of Systems for integration of functions in a complex product.

To many engineers are to functionally specific and need to back off and view it from a systems perspective. The best engineers have this ability and often allows them to advance faster.

The NASA definition describes offshore & subsea production systems even though they aren't as sexy as the ISS: NASA Systems Engineering Handbook: "(1) The combination of elements that function together to produce the capability to meet a need. The elements include all hardware, software, equipment, facilities, personnel, processes, and procedures needed for this purpose. (2) The end product (which performs operational functions) and enabling products (which provide life-cycle support services to the operational end products) that make up a system."

Formally, in the context of ISO13485 Medical Device standard and FDA Requirements (21CFR820). Informally, through OTJ training.

Oil and gas industry lacks automation engineers and typically farms them from EE. Mechanical engineers can do this too with a better understanding of the big picture.

I spent the last 13 years of my career working in an 'operating management system', which incorporated many of the concepts included in the questionnaire. There are many related concepts but in my experience the phrase 'systems engineering' is less prevalent in industry than others; specifically various versions of Project Management, Operating Management Systems and Quality Management frameworks.

I don't recognize the second - fifth terms above. I consider systems engineering as a comprehensive set of skills related to systems needs identification and using value engineering and systems analysis to solve problems and develop functional system design

Definitions would be helpful. Enterprise systems for example to me is more software systems. Is that the intent?

I generally think of them as pretty much the same things. It is simply mater of applying layers of abstraction to solve problems in different technology areas: software/IT, vehicles, etc.

The system categories as named above are very abstract. I'd suggest better clarifying such as including examples. Sounds like you may be implying the idea of a narrow functional group vs a broader department vs a corporation vs an enterprise of customers/suppliers.

Implement concepts of ownership, leadership, and relationship building

I developed many variation of systems for buildings based on owners needs. Evaluation of cost performancecopatibility with other components were regularly done although not in a formal manner

I worked as a rotating equipment engineer and the auxiliary systems used are essential to the reliability and availability of the equipment. If that's what you mean by 'systems' then I'm all for offering basic training at least as an elective.

Enterprise Integration would be better learned on the job than in Undergrad. The rest are skills that would benefit graduating engineers as a good population will enter relevant roles someday.

I have designed systems all of my career, but the terminology used in this survey is not terminology I would normally use so my answers to the survey questions may not be as applicable as you would like.

This has been my experience as an Aeronautical Engineering Duty Officer w/in the Navy, and then after military retirement working as a support contractor for the Navy doing the same work before I retired from the military. At the undergraduate level I would say it's beneficial to understand system concepts and overview of Systems of Systems, and maybe an overview of the next 3, but it would get to be too much to delve much deeper into Systems engineering at the UG level.

-

Graduate Studies in Electrical Engineering from the University of Maryland

Everything I have ever done from design engineering to marketing to sales to management to business owner has involved understanding that very few things operate alone. That is both people and machines and machine components

A pop up window for each of the listed competencies would help you receive more clear responses for those that may be unfamiliar with the rigid jargon used herein. The post-graduation column does not clarify if the desired response is the most recent use of these concepts, or rather the first use of these concepts, post-graduation.

My work is cutting edge across multiple platforms and systems (I'm a lead technical engineer in several areas). That being said, this terminology, while used, is not particularly defined for me.

Including how various components of a system integrate with each other, and with other branches of a company are very useful in the real world. For example, you can have your design as perfect as you want it, but if the company can't sell it it's not useful.

Section 2- Lifecycle Design Area Free Response

The following are text responses entered by participants when prompted for comments regarding the listed competencies in this area. No edits to the text have been made.

See last comment on previous page

I the cases above, I am framing "Able to Execute" in terms of managing/overseeing the task rather than doing it explicitly. Regarding the "No's" in the UG curriculum column,,, these are "no'" because they are far too industry specific. It would not be possible (in my opinion) to cover these effectively. That said, exposing students to some case studies examples within some of the traditional ME curriculum could make the sophomore/junior level class more relevant. I like the B-School method of using case studies to put course material in perspective. This was also well done in my MS level Failure Analysis class at U of M.

We used these concepts to define success criteria for new prodcut development under the heads of PLC (product life cycle with Stage gates of our lastest embidiment of system development we call PDE or product development engine. If an engineer is not going to design equipment especially for a competitive environment, this might be less value but is certainly valuable as you think of how to develop a successful product. We use scorecards to compare a new prodcut to existing products to test the attractiveness of the new design. We also look at design for cost and design for relaibility which are often afterthoughts if you are trying to design a product fast.

If you are using this survey to get rid of the 2 semester MEEN Design classes, you are heading down a wrong path. That was the most useful class in that it taught me how to integrate all the mathematics and sciences into a useful product and how to run a project! Keep the design class.

One of the biggest shortcomings of my undergraduate experience was the lack of education towards machine design and reliability engineering. These should be courses instead of on the job learning

No comments on these competencies

Some of the concepts should be included in a graduate school curriculum, not UG. That is why I put "No."

same answer

Design for considerations should be taught as a concept, but since different industries have different standards for "reliability, manufacturability, etc..." it should be something better learned at the industry level. Similarly with respect to technical specifications , system robustness and interface requirements. They should be presented conceptually with industry examples for case studies, but not to the rigorous degree as other concepts like "Stakeholder Expectation Definition, Functional Analysis, Requirements analysis, Concept Generation, Decision Analysis/Evaluate solution, Modeling & Simulation". The latter concepts are things Engineers going into industry should be well equipped to execute.

I think all of these are covered in MEEN 401 and 402.

The stakeholder expectation definition requires on job experiences specific to each stakeholder involved - owner, operator, business performance, etc.

Unless the curriculum has changed since I was in the undergrad ME program, various ME classes did cover a majority of the competencies listed above. Today's products may require more exposure in the engineer's education to concepts such as interface requirements.

Hardly any of these 'system' attributes were taught in the ME curriculum in the 1970's when I attended. Most of my applicable skills / concepts came from MBA classes in the mid 1990's.

Some topics may need to be awareness!

Each of these competencies is an essential component of project management at NASA.

same comment as before on numerical competency scale

I think one class can explain all the concepts above. I have found that I have used some of these concepts not realizing so it’s definetly good to know but don’t need to be an expert unless you’re going into a systems engineering role.

These to me are the more practical concepts that I would expect a new engineer to be familiar with. Most of these are fundamental to being an effective engineer who can problem solve in an effective manner.

Some of this was covered in undergraduate senior design. However, I had no concept at the time of the overall execution of these concepts in a formal systems engineering process, which is absolutely essential in engineering complex aerospace systems. I learned of systems engineering as a discipline only on the job, only hearing about it in passing (and in disparaging terms) as a student.

Probably more applied experience if I better understood the vernacular.

Job assignments covered a range of systems improvement. From partial rebuilds of existing production lines to specifying new equipment in new production lines.

I have had no formal training with these concepts but with 31 of my 33 years of experience as a project manager on small to medium size maintenance and capital projects I have executed many projects requiring definition of stakeholder requirements, fit for purpose solutions, economic analysis etc. I have helped train younger colleagues on concepts to develop cost effective, sustainable, reliable & maintainable designs. Do not misinterpret my answers as I have never been trained specifically but learned through the school of experience. I actually have thought that what was missing in my formal education was how to put it all together. It takes years for younger engineers to develop these skills.

I put Undergrad for these because my group for senior design was the systems integration team where we discussed these topics ... I had true practical training OTJ

All of these are very helpful, if not necessary for in-depth specialization. Recommend looking at DAWIA courses and Progam Management Institute PMBOK for

None

Courses in proper Stackholder Identification and in DA never hurt anybody. Any more than that at the UG level gets into my previous comment. People in the position I was in were not even considered for the position with out 15 years experience in several parts of the decipline.

At Chevron, stakeholder management, concept alternative Identification and evaluation, and decision making/analysis is core to everything we do. Being able to execute these competencies coming out of school will enable ATM engineers to differentiate themselves early in their careers. This head start will lead to greater opportunities early in their career, creating the potential for a steeper career trajectory than their peers.

A lot of what I am reading about above is more of the practical application of engineering in today's industry, while i admit i was pretty burned out by my senior year of school, i don't feel like i got hardly any "practical application" education while in school. I am certainly in favor of a shift in that direction.

Great cross discipline senior design course led by R Chona in 1999-2000 with Electrical taught these basics.

Most of this is already in the curriculum, at the senior level. The only trouble with my data is I got stuck in a job that uses none of it.

Hard to go deep in all of these areas in a high level design class. However, good exposure to these topics goes a long way to building engineering leadership.

see first comment above

I have not idea what the "ilities" are. This is jargon... In my opinion my undergraduate degree was pretty good for functional analysis and requirements analysis but less so on interface requirements. As a general note, at least back in '85, the education was aimed at making everyone a design engineer but very poor at training engineers to design things that could actually be built.

These are key areas of ensure that a system's specifications meet the requirements. At the very least discussing the concept of system life expectancy and that the more critical or complicated a system is the additional cost for operating the system should be addressed through course work.

Design Consideration for "-ilities" - I wish I had more exposure to this in UG ME. This is a key part of my job and I had to learn it early on. I think for manufacturing, which a lot of our graduates go into whether O&G or Chemicals or whatever, this is a key skill set and MEs need more education. I see this more in our "technology" degrees and Ind. Eng. than ME, and maybe it should be expanded or at least covered better. I don't remember this being in the classes I took.

Being able to solve problems using product & business combinations is key to solving big problems. I also have a masters in business.

Being exposed to these concepts would be beneficial to ME graduates. I remember being exposed to several of these concepts during our JR and SR design project teams. As my career progressed, I found these concepts being honed and refined on several of the project teams I was assigned.

Some of these would be difficult to teach/difficult to learn without some experience. For example, functional analysis may require application specific knowledge that isn’t taught in college.

Many of these concepts are project management functions however the technical aspects should be understood by the engineer and the engineer should provide input, guidance, credible challenge.

in the 1980's, A&M did NOT offer systems engineering or engineering economics - this is a good step forward

Most of this can also be called project engineering and be put in one or two 3 hr class unless it's a degree.

Again, formally through OTJ training on ISO13485 and 21CFR820 medical device design and development.

Stakeholder anaylsis is key. This is hard to learn in school without having the broad understanding of how work is is done day to day

Most of these concepts were addressed as part of project management, where the use of a stage-gated approach was used to create natural breaks and approval decisions for projects. The stage gates were defined by these aforementioned design requirements.

My education at Texas A&M was lacking real work application, i.e. design for manufacturability and assembly, manufacturing methods and the pros / cons, analysis process (rules of thumb, hand calcs, rough FEA, and then intensive FEA). Lots of theory, but not much application in school. Need more hands-on classes, build what you design, test what you build. This needs to happen earlier than senior design project, and MUST happen in a senior design project.

Good

These are more familiar than the first set.

Implement serious budgeting into curriculum and study of tax code

Same comment as before

Again, am familiar with these in light of experience in Engineering Duty Officer,and post military work experience, especially in the Naval Acquisition world. Not sure all of these concepts are attributable to UG ME degree requirements though.

-

A pop up window for each of the listed competencies would help you receive more clear responses for those that may be unfamiliar with the rigid jargon used herein. These examples are easier, as they were used in senior design classes, but it still could be opaque. The post-graduation column does not clarify if the desired response is the most recent use of these concepts, or rather the first use of these concepts, post-graduation.

See previous comment. This terminology is used a lot, but not uniformly understood by all using it. The biggest thing needed in engineers today is the ability to critically think and to have good problem solving skills based on fundamental engineering understanding. I don't know that I would recommend these things, because the application is not the same throughout industry.

Section 3- Lifecycle Implementation Area Free Response

The following are text responses entered by participants when prompted for comments regarding the listed competencies in this area. No edits to the text have been made.

Some of this gets into a lot of what we call Six Sigma statistics and operability analysis. In the job I do, on the job hands on experience is more beneficial than the statistical analysis; however, not saying there are places where that is important such as optimizing systems

As mentioned before, I think these items are highly industry specific. Some of tem could be included in an UG curriculum but not very efficiently (again, my opinion). The other issue is, what would you throw out of the UG curriculum to fit any of these in. I have been pretty happy with my (late 1970's) curriculum. I can't think of anything I would have skipped to insert one of the items above.

Some of the larger Design projects (like the NASA track) were harder to learn implementation and I had to learn it on the job - (versus the corporate sponsors track, I think they got more verification)

same

Might help to provide term definitions. Teaching engineers mathematics, phyics, etc. along with complex problem solving, logical thinking ..allows them to learn to setup good systems fit for purpose of the specific business or situation. The “school of hard knocks” in the real world will quickly show them the need for setting up systems of all types depending on the business. Projects, Safety, Reliability, Efficiency, Cost Effectiveness , etc. Typical the sytems include humans, machinery, tools, technology, etc. Maybe learning “root cause” system analysis methodology would help.... as that typically lead to system improvements and illustrates need for systems.

The lifecycle competencies listed above can be very different from job to job or even project to project for a practicing engineer. These cross-functional competencies involve communications with people across different disciplines. If nothing else, improving engineers' communication skills through public speaking classes and incorporating presentation opportunities into some classes would be a good start.

see previous comments

These are essential in program management

same comment as before on numerical competency scale

In the Oil & Gas industry, these competencies could be titled - Design, Construction, Commissioning, Start-up, Testing, Hand Over. there is much literature available in the O&G industry on these subjects.

I think the titles to the concepts (Realization, Integration, Verification, Validation) are difficult to understand, with the exception of Transition to Operation. The concepts are all valid and important but I have never used these descriptions independently like this.

Learning about the necessities of these steps in a system lifecycle was eye-opening when I started working.

Probably more applied experience if I better understood the vernacular; i.e., we do it, we just don't call it that.

Same comments as on previous page.

Transition to operation is the least important. When teaching Test & Evaluation (Verification/validation.M&S) please ensure that the independence of T&E from SE is stressed and that the item failing a test generally means the item failed not the test. Most engineers feel a test failure means the test failed, when it is usually the opposite.

Many of the systems concepts described were taught by Dr. Aaron Cohen when I attended TAMU, which helped me do my job was as a design engineer in aerospace. Although I am not a "systems" engineer per se, systems concepts can be applied to just about everything we do. One not need to work as a systems engineer to have an appreciation to a systems approach. This is becoming more prominent in the aerospace industry, the systems approach, which I believe TAMU (Dr. Cohen in particular), prepared me and others for ahead of its time. The systems approach to design solutions has been used by NASA for quite some time from what I recall. I highly recommend some level of systems engineering coursework for all mechanical engineering students.

I said yes to Transition to operations as this is often a weak-point, but all the negative responses for an UG curriculum come from my first comment. Until you understand a topic well enough to get into the detail or Realization, Integration, Verification and Validation you are teaching about something the student does not understand.

All competencies are part of the typical system design and delivery process. Being able to execute these competencies enables efficient system design and delivery. In a manufacturing environment, these competencies are developed early in an engineers career and evolve over time. At an Operator (Chevron), these competencies are only developed if the engineer is lucky enough to be assigned to a scope that requires their execution.

System testing and transition into normal Operations was a gap in undergrad and very important in most industries.

In my experience, this stuff is very specific to the job. In my case, everything I work with is proprietary, so learning it at school would do noone any good. You have to learn it when you land in a company.

These concept are heavily used deep water major capital projects in the oil and gas industry. Project execution.

Again, not familiar with the terms used

Engineers need to understand what needs to happen to get their designs off the drawing boards and into the real world customers' hands. For example, a very small percentage of the engineer's time in the automotive industry will be spent in actual design work. But great amounts of his time will be spent in interfacing with his manufacturing and validation organizations.

One area that was never covered through my course work was the role of build permits and how to acquire them. For installing new systems this is a critical responsibility that can generate substantial time and cost to a project if not properly prepared for. Although all states, cities, and local authorities differ in their requirements a basic general understanding of building permits and inspections could help in preparing a new engineer for a job requiring such things.

If you want to improve the ME department, fire all the student advisers, and start looking for people who actually enjoy engineering. "I like Rick and Morty and science" is not a qualification. "I like money and am good at math" is not a qualification. People who enjoy engineering will branch into systems by necessity.

Transition to Operation (aka moving to steady state or BAU operation). The engineer should guide the testing, validation and implementation acceptance. Technical aspects of what factors into a successful deployment are engineering functions. Transition to steady state or BAU are also under the watchful eyes of the engineer for readiness/acceptance.

It will be hard to include transition to operation in an academic environment unless it’s work through fruition for a Sr design project.

Basic systems engineering / value engineering would be a useful addition to the engineering training program

Bring in owners of companies and set up mentorship programs

These areas too "in the weeds" for UG degree I think.

-

See previous comments.

Section 4- Management Area Free Response

The following are text responses entered by participants when prompted for comments regarding the listed competencies in this area. No edits to the text have been made.

Your grouping structure is configured-around product manufacturing, which there is nothing wrong with; however, there are other engineering disciplines, such as construction and plant engineering, that these groupings should be to-the-point applied.

See previous comments

All the above will be defined by the employer, in most cases. These items will be imposed on the employee as she enters the door. Unless someone finds themselves starting a new company or doing a major reboot of an existing company, there will be little reason to build these systems from scratch. And if she were starting a new company, she should buy most of these from a consultant rather than create them herself (or steal someone from an established company to delegate these tasks to)..

All these topics were covered in the undergraduate design classes, but I didn’t realize how to manage suppliers until I got to the job.

Where I’ve recommended that concepts not be included, that is largely due to my belief that those areas are more likely to be driven by company/corporate culture and should be learned on the job and then reinforced by a mentor for maximum effectiveness.

Root Cause Analysis needs to be on this list somewhere.

Not sure how to answer "management" questions, as the issues are important, but managing without experience is not effective. I'm not sure how UG training here would be effective. I don't see how training would be much more than concepts. And some of this gets into knowledge of details of system. Management for the most part, understands the concepts, but struggle with the role of implementation.

A lot of these are some really advanced skillsets that take years to master and not appropriate for an UG education.

same

Engineering grads will easily learn this mostly common sense stuff. Maybe just broadly aquaint UGs with systems concepts and the literature available for support as needed.

Again, many of these concepts are specific to particular roles in certain industries industries and are often taught through on the job training. Since industries vary in how they execute some of these functions, it isn't as critical to be included in ME curriculum.

of note is that my graduate education is in Business Management (MBA) ----- not ME. Thus responses are of a more general nature and not specific to ME or Engineering.

Students need awareness

The concepts that are not recommended for undergraduate training are more applicable to post graduate. They are also ideally learned on the job.

same comment as before on numerical competency scale

Looks like a complete listing of activities associated with each system design, manufacture, and test program.

I like the alignment with CMMI terms

Tech Assessment is part of T&E. Acquisition is too employer dependent. Managing stakeholders, only the concept and importance of - SE does not control everything.

Supplier Management (Logistics) - need to understand the importance of, but supplier management is the purview of the logisticians - would put too much stress on SE.

None

I feel you are getting way into the weeds here for Mechanical Engineering and perhaps into Industrial Engineering.

Same basic comments as previously made for the other competencies.

In industry, you must know what the customer wants and not accept anything less. Quality must be built in from the initial start and inspected along the way for compliance - lost market share and profits are on the line when a $ 1 billion project is "stranded in place" because even one system is not adequately 1) designed, 2) installed, 3) documented, 4) performance tested, 5) validated and 6) perform under process control(s) . An engineers can cost too much (money and their own career) by not understanding the big picture up front. Technical acumen and competencies can be developed along the way; The focus and big pictures need to be understood.

While these are important skills they are typically industry and company specific and are best learned on the job within the specific corporate culture and work processes.

So many of these items are tied to technical management and leadership. This could be an engineering management elective set of courses with ease.

As stated before, many of these areas vary so much with organization and industry that, other than a very basic familiarization, they should best be left to OJT. However, a concept that was totally missing from my A&M education was the fact that all of the engineer's salary is, in the end, paid for by what ships to the customer in the end. So the interfaces with the manufacturing operations and the final customer are crucial to understand.

These are all key function of a project manager and were generally touched on in some amount during the senior design course.

Some of the concepts I learned not formally but as a result of team and group assignments/projects - I included that as part of UG ME Educ.

As stated before, some real-world examples would be beneficial.

While certainly useful, a number of these competencies are industry (and even employer) specific. For example, I have worked for 3 companies (each in a different industry) and have found that requirements and risk management are specific to each company. In one instance both were completely managed by one competent lead engineer without formalization. In another instance both are formed during the FEED study for a project and actively managed in-situ between all stake-holders. Having worked at both extremes I don't know that one is definitively better than the other - one is more useful when working with highly competent leadership and small project scopes (the lead engineer approach where a high degree of mobility is required, such as in an "true" R&D environment) and the other is less sensitive to the quality of leadership and more appropriate for larger work scopes (the more laborious in-situ management of requirements and risk by stake-holders).

Most companies have their own system for performing the above tasks. A brief introduction to the concepts is all that is needed.

We did a lot of this in our engineering design classes. You can't learn how to swim from a book. Design is a hands on experience.

All of these concepts could/should be covered under a Technical Project Management umbrella. Being a knowledge leader in these categories are critical to the success of an Engineer.

this is getting boring, i'm done.

I don't understand 'acquisition'. Never heard of it in this context.

Training in the basics would be helpful

Reuirements Management is usually driven by the customer, but should equally be driven by meeting company goals (ie making money). For the medical device field, Risk Managment is a very important and time consuming part of my job.

Most revelvant portion above

Maybe at the Master's level for these, but this is too in-depth for UG degree.

these would provide a leg up on the competition coming out of college and well into the future

Do not know what is meant by Concurrent Engineering. Every Corporation will have their own methodologies for configuration mgmt., logistics, monitoring, supply chain mgmt., and customer interfacing. Important for basic concepts to be taught for understanding but the corporation will train appropriately.

Apparently, I'm not particularly suited to this survey. I find most of these areas get in the way of profitable work. My work and my groups work are best-in-class regularly out performing our competitors. My company has over 5000 engineers, but these things associated with this survey are not view particularly favorably by our group. The things in these areas that are needed we already perform, but the addition of requirements along these lines seem to get in the way more than help.

Section 5- General Comments Free Response

The following are text responses entered by participants when prompted for any general comments at the end of the survey. No edits to the text have been made.

Finally, please share any general comments regarding systems engineering education for mechanical engineers.

Very Important

I am a pilot for the Navy, and have not worked as an engineer. However, many of the concepts discussed here from a systems standpoint have been useful for me, especially in my current job as a Weapons and Tactics Instructor when attempting to help build requirements for current and future platform capabilities.

A worthwhile survey, no doubt. However, in crafting an U/G curriculum, make sure that it has a practical foundation based on real industry experience vs. an academic flair.

Provide competency in GD&T for students.

It is a natural part of the way things are done now and will only increase in use. Better educated on the topic the better one can execute their role and progress their career.

It is easier to utilize a well versed ME specialist to contribute in the SE environment than the reverse situation.

Try not to impose the "charter/tracker" tasks too early in the educational stream. Engineers will find themselves surrounded by that stuff soon enough in the normal course of their career.

System Engineering is an essential integral part of mechanical engineering especially in the automation era.

I worked in construction for ~20 years - in the Navy as the Owner, for a private consultant during project planning phase, for a contractor during construction and for a residential developer managing design consultants and construction contractors. At ~40 years old, I changed careers due to a sickly baby. I now work with trees as a Certified Arborist, primarily on construction projects during design and construction.

It is easy for engineers to think about ME as hardware design based on 3D CAD. Even with broad definitions to include automation and robotics, this is a narrow definition. What are you designing as a system, how long to build a prototype, how it will be tested, success criteria, etc all all key to making a successful product. A perfect design that fails cost targets or misses a market window still fails as a product. You need to consider many disciplines in making a successful complex system. PLC is more and more critical with the complexity of the system and system requirements. I did not get involved in this topic for more than 10 years after graduation. Now to build complex semiconductor equipment, we rely on it completely to align the efforts of large cross functional teams to a staged, well defined, long term set of goals.

Although I did not learn much of my systems engineering knowledge in UG ME, I had minimal issues with learning it on the job.

Here's what I think ... my Aggie ME degree taught me haw to to fundamental analysis. In my case I specialized in thermal systems and turbomachinery. In my oil and gas career (automation and controls) I have routinely been involved in both control theory and thermodynamic analysis of gas turbine and compressor systems. The superior education I received in fundamental thermodynamics has allowed me to remain gainfully employed throughout my career. It's the fundamentals that I learned at A&M that have enabled me to develop advanced controls concepts that govern the turbomachinery. Two things ... The reduction of the degree plans to 120 hours (mine was 138) and the increased emphasis on liberal arts curriculum serves to water down the ME degree to the point where I do not see many young engineers possessing the same competency I enjoyed ... And please note I was only a 2.8 GPA, hardly a genius high performer ... But I have been able to use a natural ability to create algorithms combined with a superior thermodynamics education at A&M to fashion a career centered around automation of compressor and gas turbine systems. Just like a hitter in baseball its the fundamentals of the swing that make the hitter be able to be great. In engineering it's the ability of an engineer to apply fundamental concepts that provide the technical underpinning necessary to design superior systems that deploy advanced concepts. ... In other words stick to the fundamental tenants of the ME degree for undergrads and put the more advanced system concepts in a specialized graduate curriculum. Respectfully ... Roy

If you want to move into managerial or project positions, it is essential. If you want to stay technical or research, you still need to understand how the company expects your work to fit into the project picture.

These topics where either briefly mentioned, or not covered when I completed my ME degree in 1982. As my career advanced with higher levels of engineering management you begin to take a holistic view of equipment and systems, which, results in a system view.

Industry needs THINKERS and DOERS!

This competency is vert implortant. We hire several MEs and most will either begin their careers in Project Engineering. Having these skills will give the students a competitive advantage in Industry.

I do not perform the engineering of a project, but I must understand how all of the HVAC systems function together and relate to other systems within a project. My education at A&M provided the tools that I have applied on the job to develop the expertise I now possess. If the UG degree can provide the systems concept tools that it has taken me years to develop, the young engineers will be extremely valuable to the industry. I have found that most, unfortunately most, individuals understand their part in the overall project, but few have the drive or interest to understand how their part fits into the entire project. My job comes in as the last contractor on a project. When I arrive everyone is supposed to be complete and everything is supposed to work. I spend at least 50% of my effort getting other contractors to complete the things they say are finished.

Theory is great, but modern engineers are expected to be salesmen, purchasers, planners, manage logistics, work with stakeholders; they're the whole package. Communication skills, teamwork, and public speaking are some of the most valued skills in the positions I've held to this point.

Dedicated "reliability/systems" engineering was not implemented in my company / industry until later in my career (1990's). Definitely need curriculum to allow a graduate to attain "certification" without a concerted effort outside of their formal education. I've been retired for 11 years so I have been out of the most recent thinking on how to acquire that knowledge.

we did not go into machine or system design as heavily as chemical engineering students did. The senior design program was truly great and focused on a lot of this, however, some courses should highlight problems many will face in manufacturing and on common classes of machinery. These can be electives, I know it is already a dense curricula.

You can always teach someone business, but engineering fundamentals are harder to come by.

I think systems engineering skillsets are learned over years and most need practical experience to master. It is really difficult to teach these in an UG course. Systems concepts require a good understanding of different competencies and then applying them to solve complex problems.

Too much of the mechanical engineering degree I received was focused on detailed analysis. My industry uses specialized resources to complete these analysis, most Engineers just need to be able to speak their language and interpret their results. More higher level thinking and expansion beyond these concepts should be included. Also less "teaming" activities, I know being able to work in a team is important; but every single class forced you to do the majority of your activities on a team. This lead to A type personalities dominating experiences. People need a broader range of opportunities.

Undergrad classes should prepare graduates to work on a systems management team. They should be able to step into various roles on the team, except for being team leader, since that would involve experience.

Over my 20 years of experience, many companies across many industries have adopted standardized methods and processes used to guide their products' life cycles, manage their workforce, and implement best-practices all around. Teaching these concepts at the undergraduate level will give Texas A&M graduates a significant head-start over their peers upon entering the workforce and will serve to improve the university's image.

I worked for Hughes Aircraft in their satellite division. At this company, Systems Engineering was a path to upper management. I was a systems engineer for 6 of my 7 years as an engineer before I stepped into a technical management role. Very key to my success.

Try not to water down the fundamentals of the ME curriculum. Anchor in fundamentals of math, physics, materials, dynamics etc. By all means please keep a strong focus on written and verbal communication skills. As far as SE is concerned at an undergrad level, it is okay to introduce basic concepts of the 'V' and key activities at each stage. Stress importance of sound concept of operations (CONOPS) and requirements up-front. Introduce model based engineering (MBE) concepts. But overall, my experience is SE's are 'grown' through experience rather than produced through a curriculum-ready to go right out of school.

I think a Product Life Cycle class would be helpful in engineering to cover the basis of each subject included in this survey and to provide a general overview of the processes involved in engineering, commercializing, and sustaining a product.

Systems engineering is broad and covers many aspects of engineering. Most larger companies have specific systems processes and or software, so I am not sur an in depth systems class would be beneficial, but familiarity with the concepts and how they can improve the product/process might be beneficial

The fact that this is being surveyed is awesome. However, I believe most engineers will have little understanding of systems engineering and may answer inappropriately. Keep in mind that a job search for system engineer turns up IT positions.

If mechanical engineers want to go beyond component and product level design and into full life cycle design then these concepts are a must. Many of them are still very important to understand just for component and product level designs. As a lead SE and Chief Engineer you must have a very diverse skill set and learning all these would be very valuable.

Very rarely will you work with something that is not impacted by other elements or has an impact on other elements. Power, command and control, usage environment will all interact with a component so that all must be considered in the design, testing, manufacturing and production of the component. With automation of tasks growing, all areas must be considered to have a design that functions as intended in the environment it was intended to operate in, be produced at a competitive price, and meet customer expectations.

i learned the process under Max Faget and Caldwell Johnson while on the job. I think it is better to focus on the basics in college and learn this on the job. basics=math, science, engineer,etc.

Just have a couple of special speakers from various industries come in with one hour overview presentation. I’d say continue to train engineers and provide them the generic math and physics tools to solve any problem. Just teach them to “fish” they’ll figure out the rest.

I believe I am too far removed from the engineering education to provide meaningful comments about it. System concepts should be included early, but there needs to be understanding of the components of the system before trying to effectively understand the system.

Basic understanding of systems engineering is a good thing for UG Mechanical engineers to have, but a lot of the more in-depth concepts behind systems engineering are only specific to certain roles in certain industries and can be picked up through on-the-job training, or graduate studies. Many Graduate institutions offer System's Engineering Certificates for those interested in pursuing Systems Engineering/Systems integration roles, but for those not specifically pursuing those roles; a general understanding of systems engineering concepts should suffice.

"Including in the curriculum" could mean lots of things and many of these topics are very pertinent but not to detriment of learning the fundamentals of engineering. I can teach them configuration management, for example, but it is much harder for me to teach them to systematically break problems down and solve them piece by piece using the fundamentals.

I spent a large portion of my career in the development of new equipment systems and had to learn on the job and sometime through the painful teacher of experience. I support including this in the engineering curriculum. I would also include learning experiences that require the students to be able to think on their feet and generate some self reliance outside the computational power of the computer.

Systems engineering is defined differently by different companies. Any curriculum that is adopted should emphasize the definitions of terms to make it clear what is being talked about.

I've built my 22 year career on system engineering, technical program management and M&A activities in a couple of different industries. I feel this is one of the most valuable skills to learn.

Many/most of these skills are learned indirectly as a result of job experience even if they are not formally applied. I would consider most of these as formal managerial task, but there should still be some consideration and awareness of them at the application level to keep projects efficient.

I think systems engineering for mechanical engineers is hugely important and relevant. When I did my undergraduate in ME at TAMU in early 2000, there were a large subset of students who did not see the point and were content with designing small mechanical 'widgets'. I think in today's environment that is a very carer limiting mindset. The need to understand larger systems and operate as part of a larger system is absolutely critical.

A lot of these concepts may not require formal instruction. For example, you learn basic risk management and program planning techniques just by executing projects in school. If you are going to add this to the curriculum I would focus mostly on making students familiar with some of the standard tools/methodologies (risk cube, interface control documents, configuration management, etc.) rather than how to properly and thoroughly do formal Systems Engineering.

In my experience, the mechanical engineer is the lead engineer who brings all engineering disciplines into focus. To make his system work, he needs a proper foundation from the civil engineer, robustness from the structural engineer, needs to deliver a product or process from the chemical engineer, and have power and automation from the electrical engineer. All on time and within budget.

In systems engineering, it's very easy to get bogged down in the requirements language and pain of digging thru paragraphs to extract technical requirements. Systems engineering in this regard needs a complete overhaul. "Interfaces" between teams/companies is always difficult, and significant opportunity for error and miscommunication. Systems engineering should function to provide clear technical requirements regarding interfaces and performance.

I feel this is a different way of thinking and should be included in the curriculum

I am not an engineer but I find concepts of systems engineering to be useful when considering interactions with other practices, with hospitals, and when considering office operations and population health management.

Systems Engineer makes for a "complete" engineer, better prepared for business and industry. It informs a decision making process that is functional and risk-based. Engineers need to be ready to implement the basics of Systems Engineering just as they need to implement the basics of applied physics and mathematics. The inability to define the "what" before the "how" wastes time and money. In addition, it promotes thinking/perspective at successively higher levels, better enabling engineers to communicate and speak to all levels of management for buy-off and decision making.

The all-around mechanical engineering program prepares a student well, even if the systems engineering concept may not be familiar to a new ME grad. If one expects a mechanical engineering student to be well versed in all system engineering concepts when s/he graduates from an undergrad ME program, the curriculum would need to be much longer, and thus not affordable to the student. Would you consider offering a 5-year program that has 4 years BS program in ME and a 5th year MS in Systems Engineering?

I may not be interpreting your titles correctly but we did a lot of similar sounding stuff while working in Six Sigma.

Mechanical engineers must absolutely be sound in the fundamentals - machine design, thermal science, and others, but the practice of engineering requires competency in the systems engineering disciplines. You have done a very good job with this survey!

I think this is a good area of focus to improve the curriculum. Most of what I learned here came from on-the-job training and experience. I now specialize in this area as a part owner of a small engineering company. I would suggest a real-life engineering project in cooperation with an engineering company to help expose students to these concepts practically. A similar survey could be sent to prospective cooperating companies to suggest partner projects by identifying which of these concepts would be applicable.

Most companies have a specific way they like to mitigate risks, apply the "ilities" and monitor their projects. While it may be helpful to be exposed to these things during undergraduate study, many companies will prefer to give engineers local training.

I worked as a mechanical engineer in the Oil&Gas Industry, specializing in Rotating Equipment. All of these competencies in your survey are used by Rotating Equipment engineers. The annual Pump and Turbo Symposium sponsored by TAMU deals with all of these competencies; the papers published by the symposium should be good reference material.

I think mechanical engineers should have general knowledge in systems engineering.

As a product development engineer for my entire 7 year career, these concepts are very relevant. I would say that upwards of 60% of my time is devoted to concepts such as these. A learned and trained ability to manage multiple projects that are all part of a complex system of projects would be very beneficial coming out of college.

I think a light touch on these topics is useful, but I wonder how effective a discussion can be held in a classroom due to the diverse industries and resources MEs work with.

Most of what I've learned about Systems Engineering came from Design for Six Sigma.

I am an advocate for incorporating systems engineering in the mechanical engineering curriculum and have even tried to convince Georgia Tech (where I received my Ph.D.) to work in this direction. Even though it is not obvious to many MEs working in industries where SE is not a formal practice (I work in an industry like this now.), I find it is essential to understand and practice these concepts and makes me a better engineer and manager. Please feel free to contact me to discuss my thoughts. Nicole Martin - 404-202-3793

It is important to establish what the life cycle expectation is for the required system. This is key in helping to determine the most return on investment. Without a clear mission time there can be over engineering performed that can easily overcome the potential benefit to a project.

A general awareness of each of these things would be helpful. The real world will provide the details.

I have moved into the field of systems engineering, and I find that my mechanical engineering background is vital to being competitive. I can understand physical systems much better than many competitors. However, not all MEs will need these skills. I think adding an elective track toward SE might be a wise approach.

My experience is more operations in nature. For those who intend to manage people who are operating systems, a more apprentice-like education is my perspective.

Tagging on to my comments earlier, developing a project, obtaining approval, following through the engineering phase, overseeing construction, managing costs, contractors and keeping management (stakeholders) informed takes a typical new engineer years to develop. Formal training as a college curriculum is a step in the right direction. I would caution; however, to avoid missing the forest for the trees. Concentrating too much on the theoretical concepts without practical examples can be a detriment. I would think very few graduates will go one to manage mega million or billion dollar project. Many, like me, will manage small to medium projects, where the project manager will be expected to perform ALL the functions described and thus will need to understand what's important and when items become critical. I applaud the effort to develop systems engineering but caution to not lose sight of practicality.

As I filled out the survey, it has been difficult for me to understand the domain of systems engineering as perceived by the study author. All of my study entries have been outside of a dedicated systems role, but have been adjuncts to a role as an R&D engineer (mechanical focus). Recently I was assigned to a dedicated R&D integration role for corporate acquisitions, which contains alot of systems engineering activities. However, this is a pretty small part of my career. I would recommend something of an Intro to Systems engineering class. Nothing more unless the student is specializing. In our (Fortune 250) company, only a small fraction of the R&D engineers are assigned to systems integration. There are no dedicated systems engineers -- integration is accomplished by senior staff for each functional group.

Many of these topics are great topics. Not sure how to jam them into an already-full curriculum. Many of these topics also need to practical experience to learn them. It's very hard to really understand how to manage diverse stakeholders in a project until you have done it in practice.

Important to realize that business practicality and economics and risk management govern the use these concepts.

These skills translate well outside of typical Mech engr roles - I find myself relying on them quite a bit in my new career within financial services industry - systems are everywhere

An overview would be helpful, especially for those of us that were not design focused, but more system and analysis focused. ME provides a great background, and this type of course would help to bring it all together.

Strengthening SE education will enable the university to produce more capable, productive, well-rounded, workforce-ready engineers who will have an instant leg-up on their peers. SE education is critical if TAMU wants to continue to be known as one of the nation's top engineering universities.

This is really something that I am not familiar with. Sorry about that.

Systems engineering is the lynchpin between modules of work that brings it all together into a success or allows it to fall apart as a failure. Most of these concepts seem vital to completing a project, and there should be more focus on it during coursework.

Please see my earlier comments.

MEs are usual great technical managers, functional or project due to more general technical skills as compared to other degrees. A course in SE would be very beneficial for MEs to specialize and more rapidly advance into Systems and Chief Engineers, Project Engineers and Program Managers

I graduated in 1980 from TAMU with a BS in ME; I worked one year for the Engineering Dept. of Lower Colorado River Authority at a power plant before going to seminary and eventually being ordained. I have used the problem solving and prioritization learned at my TAMU engineering classes extensively from everything to personnel placement/development, to program/project planning, to physical plant maintenance/acquisition, to homily preparation. My ME degree has been more important to parish administration and pastoral ministry than I ever imagined 31 year ago. Edward Winkler '80

Please refer to my comments from the prior section. The systems engineering approach is used in my industry. One not need be a “systems engineer” to understand and practice the principles. An understanding of systems and breaking things down to something as simple as a “need statement,” and then coming up with need analysis, performance analysis, function structure, functional requirements, performance requirements, understanding risk for various trade studies, etc are all highly valuable to a design engineer. TAMU did a great job in preparing me, much more was learned on the job, and I believe at least an introductory course in systems engineering would be highly beneficial to all MEEN students.

Being a Dept of Defense employee (active duty Air Force officer, 'Developmental Engineer'), familiarity with systems engineering concepts and their role in the Defense Acquisition Lifecycle has been a core part of my job since I commissioned. I think a basic SE course as an elective for senior engineering students is a must for any modern engineering program (whether it be Mechanical, Aero, or EE). As a senior at A&M, I was exposed to top-level SE concepts as part of our senior design course. I found the frame of reference that course provided to be very useful as I began learning how the DoD designs, builds, and employs all manner of complex systems. Cool survey! I hope you're able to use the information to make the A&M ME degree even more valuable!

-I am biased by my work, oil and gas firm plant design, construction, and commissioning. -Would prioritize traditional technical subjects but would have appreciated and opportunity for elective classes on systems engineering. -Not all firms are driven by systems engineering processes and on the job learning was sufficient for all of my requirements. -Good luck with your survey and research.

While i did spend my first 4 years as System Engineer, most of my experience has been centered around design and upgrades of commercial nuclear power plants. Many of the concepts discussed in this survey are directly applicable to the softer side of design (ie understanding the system(s) you are affecting, understanding the needs of the end user, validating inputs and verifying results through testing.)

I only worked in Systems Engineering position for one year, my first year in the USAF, at Kirtland AFB NM working in the Air Force Weapons Lab - test design and data acquisition with EMP.

I participated in Foundation and Chona’s senior design courses which forced us to think outside of Mechanical only and gave us the appreciation for a wider technical viewpoint in the design process. The MSC gave me real-world business skills. The academic and non-academic experiences were complementary. It is important to continue to focus the undergrad academic experience on developing core discipline knowledge while encouraging students to get the broader worldview through the upper level design courses and co-curricular activities. A&M’a strength in co-curriculars should be leveraged for the enterprise-level thinking skills that are required in today’s graduates.

I think all aspects of systems engineering are a great background for ME's to obtain. While they may not get an opportunity to apply the concepts until later in their careers, an understanding of those criteria will serve as a great benefit in the development of good engineering fundamentals.

Systems engineering is important but needs to be kept mostly in a technical stance for under graduates. Modeling and management items should be post grad exploration and study.

There needs to be more engineering specific economics and management curriculum in all engineering degrees. I can see that there were several questions straight from the PMBOK book and PMP certification curriculum. Teaching many of these concepts to undergrads could give them a head start compared to other new grads who do not have this knowledge.

System design and integration is very important. Unfortunately, people who make equipment do not focus on such issues. Consulting engineers in turn make lots of money from this issue.

It seems like teaching general concepts at the undergraduate level would be beneficial, but given the disparate requirements and approaches in any given industry, detailed instruction without an in depth understanding of the product is not a good use of undergraduate time/money.

A lot of this is very situational or dependent on the job. If y'all are planning on putting together a class or classes for this, make sure to keep it super general and make it clear most of the specifics have to be handled by employers.

Systems engineering is closely linked with front line technical management. A Mechanical Engineer trained in systems engineering has half the skills needed to be a good leader. The soft skills tied to encouraging and guiding technical field experts bring the other half of the skillset.

See my other comments, would highly recommend this be included in the curriculum.

Today, most jobs titled systems engineer refer to computer systems. Which is not related to what I do. Systems engineering, as I know it, refers to the design of all systems within a process facility. The ME curriculum that I went through did not specifically cover any of these concepts directly, however, the ME curriculum, I went through, gave me sufficient education / background to perform this role. The concepts mentioned in the survey are all potentially important but will be learned on the job in the role I performed. It would be difficult to cover these concepts in a manner that is relevant across all industries in a semester.

all engineers need exposure to this since they all work with and need to anticipate management needs to accomplish resolution / implementation of problem solutions.

It is absolutely vital that every graduate understand how their work will be realized. How will it be built? By what processes and what can those processes actually do? How will it be packaged and sold? How will it be used by the end customer? All of these are critical for an engineer to understand! (And yes, I have actually had graduate engineers design products that could not be manufactured by any known process and/or generate drawings and mathematical/digital models that no one could interpret in this reality... So a grounding in the real world or manufacturing and integration is important!"

now that i've answered the questions, i think i could change my job title to systems engineer :D based on my career experience (high tech manufacturing and supply chain management, followed by enterprise computing service delivery), being exposed to these concepts in the engineering curriculum would have been helpful.

General knowledge and execution of a project was limited to the senior design courses. Looking at the practicality, I understand this and do not know how it could be effectively added into additional course work outside of an MBA or project manager course; however, these are important subjects as they relate to industry.

I think it is clear some of these concepts are used early on in career and not truly well-covered in our curriculum. For concepts that are found later in career - I could see that being covered in a course for familiarity or at the graduate level. It would be an improvement, but I wonder if the value is there for what is limited time in UG Engineering to cover the other "basics" they'll need when they graduate.

Adding these competency's to the ME curriculum will help ensure graduating MEs are considered for more than just traditional hardware design jobs.

It'd be great to include a single course that touches on many of these topics.

I think systems understanding with integration concepts would be valuable. I would definitely include decision analysis concepts in the curriculum.

Other examples of systems could include analogies from sports (i.e. football or baseball) and the military. It is important for ME graduates to understand the "big picture" or primary objective in addition to their role in the organization and/or system. Finally, it is important that ME graduates learn the concepts of managing stakeholders and gaining stakeholder alignment while in college. Mastering these two concepts can determine the success of one's career and must be practiced frequently.

My experience is quite different since I came out of college and went right into an electrical role. Additionally, a systems focus may greatly depend on the company. I didn't do much systems work until I went to a different company.

The best systems engineers that I 've worked with doggedly hold the sub-system teams to the understood requirements and force the separate teams to also focus on their interfaces, maintaining good communication between the various sub-system teams. It's not immediately clear to me how to teach this in an academic environment, excepting the understanding of how how sub-systems may interface.

Much of this was touched on through our Senior Design Project rather than any specific classes. I think that was a good way to handle it. However, I don't think that extra classes should be added to replace that. If anything was lacking in the curriculum (and i see this more so in the younger engineers that I've worked with) it is practicality and the tools to tackle new problems that they've not been exposed to directly through curriculum.

Learning how to integrate systems is a skill that was acquired through trial and error in my experience as an engineer so far. If would have had school projects that were more systems management oriented, I feel that I would have been more successfull in my earlier career.

If You plan to evolve from a design engineer into project management, This is essential. If you plan to evolve into a subject matter expert it's still a nice-to-have.

Systems design, engineering and integration is more about working as a team and communication than anything else.

Systems engineering has broader than the traditional industry applications. In the Semiconductor industry, the market is moving towards a system level solutions vs individual device level. For mechanical engineers, this means more thermal, mechanical and some electrical considerations. Semiconductor module packaging for applications such as IOT and Automotive have become critical. Let me know if you would like me to give a short talk on this industry area-mark.gerber@aseus.com

The impact of the internet (IOT) and cheap computation will make a big change on how systems are viewed, developed and managed. Almost all disparate parts are linking together so systems engineering will likely be a dominant competency to have and develop for a sustainable career with algorithms being an important tool.

I think it is critical for students to have a solid understanding of the entire engineering system to prevent the common mistake of engineers working in "silos".

I would not call it systems engineering education. That's not what it is. It's a Technical Project Management role (see PM-BOK) and the engineer is a key contributor/stakeholder. Good luck.

Back in my day (1997 graduate), there was too heavy of an emphasis on manufacturing/design. Would have liked to have other tracts besides just design, particularly a Construction/HVAC tract.

good idea - must teach the "ilities", economics, trade studies, risk management, etc. As ME's we still must focus on technology and technical integration but exposure to systems engineering is a must. SMU offers a masters program in SE.

The young engineers are well educated in the theoretical part of engineering. but they seem to lack the knowledge of how theory applies to real life equipment and systems. Teaching students how to apply the theory to an actual piece of equipment and or system would be a great addition to the curriculum.

This is not an area I have much exposure to in my role as a structure analyst. This is an area I wish I knew more about.

It would be good to have an overview course in systems engineering as part of an ME curriculum as an elective at both graduate and undergraduate levels. I do not recommend a full degree path option. The time is better spent in core engineering technologies. Lockheed Martin Missiles and fire control looks for depth in core skills, not an SE degree.

While I feel that systems engineering concepts are best learned through work experience, I agree that more of these concepts should be included at the undergraduate level. It would be valuable to include perspectives from the software development community, such as DevOps, as an alternative to the traditional "waterfall" product development life cycle.

When I graduated from A&M, I had not had many computer courses (I mainly used slide rules). In my early career, my employer was using computers to simulate various technologies. Overtime I became very familiar with computer systems. Currently I develop simulation models. In today's age, systems are an integral part of engineering and business. A must topic for engineers today.

On the job training makes sense as different companies have unique solutions and practices

I would also consider incorporating knowledge and language associated with technology readiness levels and production readiness (or something similar)

Currently working with the University of Cincinnati Co-Op program. This program is fantastic for getting students acquainted with real world scenarios to apply the skills they are learning. I recommend looking to this program as an example for students to further their education.

It is important because it is applicable across all technical professions and disciplines. In industry, it takes more thank just mechanical engineers to deliver on time, under budget and to the customers satisfaction.

Systems engineering is a major factor of any engineering field at some point in time, if not regularly. The material I learned as an undergraduate, paired with the information gathered in my first two years in the field has prepared me to succeed in most general systems engineering functions. The more basics that can be covered in undergrad curriculum, the better.

I think incorporating an introductory systems engineering course into the mechanical engineering curriculum would be a great way to help prepare students for work in industry.

Feel free to contact me for more information at 281-380-6548. I'm more than happy to elaborate.

I am a former Associate Professor of ENGR 111. I was surprised by the amount of industry-readiness NOT being built into the curriculum. Most graduates will work within a 'system' of some type; Total Quality Management, Management of Change, OSHA PSM, Operating Management Systems or 'Lean Manufacturing' constructs for examples. I live in College Station still and think I have something to offer in this conversation. Please contact me if interested.

I'm not sure how all these things can be taught and understood properly in a 4 year span. These are all critical for a well rounded ME to understand. Systems Engineering is a tough roll when designs go well and even tougher when things go wrong.

GE would be a great company to benchmark for these subjects.

System engineering tends to be a senior level job, and the first 5-10 years on the job are often focused on sub components of the system, with requirements defined by senior systems engineers. I doubt that formal training in systems engineering at the college level would enable a graduate to go straight into a systems engineering role, lacking actual working experience with system subcomponents

A single mandatory systems engineering class would be beneficial, but should emphasize putting a design into production, and what that costs from cradle to grave (money, resources, etc). All engineers should know how to assist a project manager in planning a schedule and budget. However, I wouldn't push too hard on this education as the best experience is running a real project with a budget and schedule. It might be worthwhile to offer a systems engineering minor at A&M if it isn't already offered.

I moved from ME to SE to Program Manager. Preparing MEs to think at a system level is beneficial for preparing them to be effective in working with others in the workplace. I've seen too many MEs (or EEs or other engineers) who only think about their own discipline and end up with designs that aren't producible or systems that don't meet requirements because the individual components weren't developed as part of the greater system.

Students would be well served by understanding the basics of systems engineering. As they progress in their career, understanding that the processes by which large complex systems are created are very different than creating a widget. This helps them to become much better cross discipline leaders.

Mech Engr are well suited for systems engineering with our broad technical background. Better training for interfacing with other disciplines and management would improve effectiveness.

Mechanical engineering is systems engineering. It is about knowing how all the things work, what the interpendancies are, and how to get people to tell you what they really need versus what they think they want. Systems Engineering is just engineering management. By educating students to be great engineers, you will get the systems engineers you need.

System level thinking is essential to being an effective and competent engineer, a skill a majority of engineers lack when graduating with their undergraduate degree. Adding undergraduate classes and projects that encourage system level thinking would be beneficial for new engineers and enhance the undergraduate curriculum. Systems level engineering classes should also consider cross-functional engineering disciplines, e.g., petroleum, chemical, and electrical, as well as science based disciplines, e.g., geology, physics, etc. An engineer that knows how to integrate across disciplines is invaluable and a much better engineer.

I believe systems engineering concepts should be a single class in UG ME curriculum. Anything past concepts is a waste since specific systems are very dependent from industry to industry and company to company.

Find a means of becoming an other even if not in engineering field. Ownership will produce a life and lifestyle for greater at magnitudes that being traditionally employed do not offer.

May consider offering courses or a track on project management.

My responses are based on the application and integration of my undergraduate studies in the context of my career. I am a senior database and system administrator at a software company with a large client base, both small and Fortune 500 companies. My role is extremely flexible because of my ability to learn new technologies quickly, integrate with and improve existing technical solutions, and generally being able to troubleshoot almost any problem with no prior background or specific knowledge. I attribute much of this skill to my training as an engineer. As an ME, I still often felt like a "systems" engineer when around other engineering disciplines. The mechanical engineer must know something about everything - and when you don't, you must know how best to find that information and apply it correctly. More than ever, my job requires elements of system engineering at almost every level. I write code, design solutions, and solve technical problems - but I still think like an engineer.

It would be appropriate to teach within the parameters of ZERI (Zero Emissions Research & Initiatives) and the Blue Economy as taught by Gunter Pauli.

This seems like a great idea. I ended up getting a M.S. in Systems Engineering and it made a huge difference in my career and capabilities. I strongly recommend including an SE class in the MEEN program, or at least concepts of SE.

I have worked for 32 years for General Dynamics / Lockheed Martin Aeronautics on multiple development programs for fighter aircraft. Though most engineers from my generation in my industry came from the more traditional ME/EE/Aero disciplines, it is important for TAMU to note that some of the highest-paying jobs in my field carry the title of "Systems Engineer". I note that few colleges are offering undergraduate degrees in Systems Engineering but that there are a few offering master's degrees. I feel strongly that it would be beneficial to ME undergraduates to get more exposure to Systems Engineering concepts to equip them to be successful beyond the traditional individual-contributor roles of design, test, and analysis. We are increasingly working for customers that provide requirements for programs/projects that need to be managed across multiple time zones due to global partnerships, and Systems Engineering, which was not a term that I was exposed to in the early '80s during my time at TAME, is an important discipline for success in complex programs/projects.

Very important in senior engineering roles in EPC project environment such as oil & gas

All of these concepts would be helpful to have in an ME education, but in a BS program, they should probably be at a survey level to simply address what they mean, why they are important, and how to find information on how to apply them. I worked with most of these during my first year after graduation without any formal education addressing how to do them well.

Students should definitely be trained in these subjects in undergraduate classes, especially in mechanical engineering. As a lead engineer/engineering manager, I witnessed firsthand that very few universities are training UGs to understand concepts such as: design for construction/fabrication, product/concept implementation and balancing expectations of project management. If TAMU were to implement a program that trained UGs to be able to apply these concepts successfully we would further raise the already exceptional quality of engineers entering the workforce.

best taught thru real world examples in various industries

It will all depend on the role of the engineer in the marketplace. Personalities will dictate if an individual is suited for component design and system design or developing more customer interfacing skills and having the ability to understand complex systems and the measured impact on a business. I was lucky enough to do both, and believe their is a role for both. Except for very specific application areas most "ideas" are only as good as they can quantified and leveraged in a business environment. I believe adding a marketing and selling class, taught by industry specialists, would be most appropriate.

Most companies have specific people for planning, buying, sourcing, and drafting/modeling. Engineers just need to be able to give a realistic estimate of how long tasks will take (this is harder if it's R&D, which does not tend to run on a linear project schedule). For requirements, they need to know that the customer isn't always right. As the engineer of the product, you know it better than they do. Listen to what the customer thinks they need, and try to decipher what it is they actually need. What they say they need and what they actually need may not be the same. The goal should be customer success. It's also important to learn how to creat "SMART" requirements that can't be interpreted differently by different people, and how to lock in certain requirements throughout the design (such as key interfaces, so you don't accidentally change one while another group is developing the mating piece, and then end up with two components that don't fit). Clear, honest, and open communication is key for all of this.

For the most part I feel the technical knowledge I learned in my undergraduate degree was the most important. For me, the management concepts in building systems come naturally once you first understand the technical aspects of the system. Technical understanding is the basis of what gives you the confidence to manage and lead the development of complex systems. On my recommendations for ME UG curriculum I tried to favor items that I felt improve technical skills as oppose to soft skills.

I think it is very important, but not necessarily s much for the rigidity of the concepts so much as the ability to recognize the importance and impact of these aspects on the successful execution of complex technical projects. The Formula SAE and Formula Hybrid teams were a great wealth of this learning for me, personally. The normal senor design classes more or less paid lip service to a few of these concepts. Students need to find an outlet to pursue real projects with real consequences to truly appreciate this approach.

I'm sure you are doing a fine job in this arena, but the one-size-fits all nature of the application of many of these things makes them extremely inefficient. So, again, my answers are probably not worth much. Thank you.

Engineering students don't know what valves, pumps, motors, pipes, controls, etc. look like, what the do, why they are needed, etc. We ask simple system design questions in interviews and only 10-20% of students can describe standard components that make up a simple system. How do you make water move through a pipe? Most Jr-Sr level students cannot answer the question.